

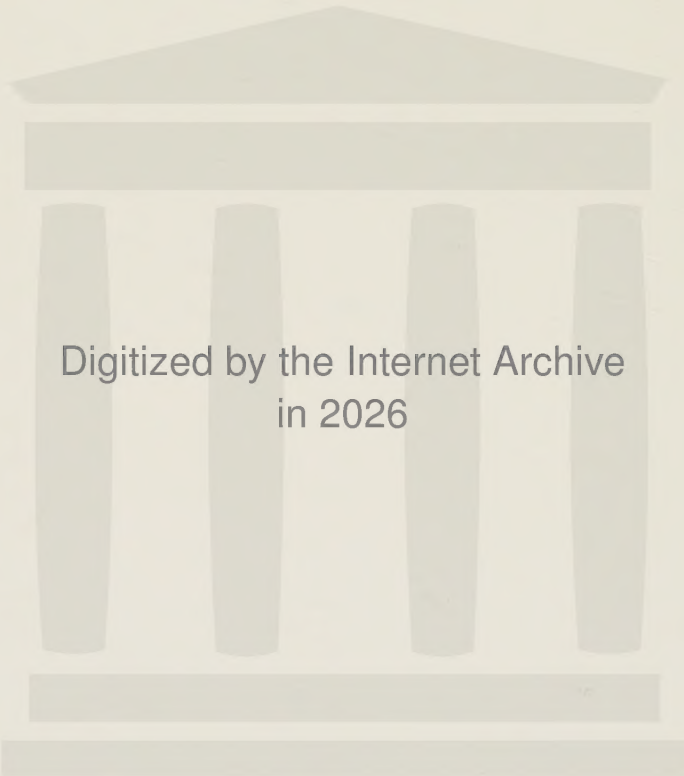
INK JET PRINTING
WITH
MECHANICALLY DEFLECTED JET NOZZLES

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LUND - SWEDEN



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vid tekniska fakulteten vid universitetet i Lund
kommer att offentligen försvaras i sal E: C,
Lunds Tekniska Högskola, måndagen den 29 sep-
tember 1975 kl. 13.15

av

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Report 1/1975
Department of Electrical Measurements
Lund Institute of Technology



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SUMMARY

In this paper the use of a mechanically oscillated ink jet in printing systems is studied, the intensity of which can be controlled by electrical signals. The intensity modulation is based on the dispersion of an ink jet into a spray, which occurs if an electrical field is applied near the nozzle generating the jet (Hertz et al. 1967).

In the first part of this paper, the fundamental aspects of this printing principle are discussed. Attention is paid to the shape of the oscillation of the nozzle. Besides this the influence of different factors, such as printing rate and paper quality, on the density and sharpness of the print out is discussed.

The second part describes three different applications of this printing principle, all of which lie in the area of alphanumerical printing, e.g. an almost noiseless ink jet typewriter which is capable of printing at a rate of 50 characters per second.

1. GENERAL INTRODUCTION

1.1. Introduction

Due to the fast development of telecommunications and computer technology during recent years, especially the decrease of cost of minicomputer systems, electrically controlled print devices have become of great interest. The reliability, speed and noiselevel of conventional mechanical printers are not sufficient for today's requirements. Consequently many new methods of printing have been reported and commercially used. Most of these printing methods are capable of printing information other than alphanumerical, such as diagrams and pictures.

The methods of electrically controlled printing can be divided into a number of groups. Two of these groups make use of an impact printing technique, namely: conventional mechanical systems using type bars and mechanical dot matrix printers, where the characters are formed by a small number of needles. Besides that, a number of non-impact methods exist, using different physical phenomena such as thermal sensitive, electrosensitive, electrostatic, magnetic, photosensitive methods and ink jets. A very brief review of these groups of print methods will be presented here.

The first group, mechanical printers using type bars, contains the conventional teleprinters and line printers (Carrol et al. 1970). A more recent construction of printers in this group is the so called "daisy wheel" (Cramer 1970). In spite of the conventional construction of these printers, they are still the most frequently used.

During the last few years, another kind of mechanical printers has become rather common. This type does not use a type bar for each of the characters to be printed, but instead the characters are formed by means of a matrix and are printed by a small number of needles

(Borne 1968). All of the impact print methods are able to print on plain paper and make carbon copies.

The next group of printers makes use of heat sensitive papers (Payne et al. 1973). One example of heat sensitive papers, that can be mentioned is a black paper base coated with a white wax-like coating. Heated styli melt the wax and thus expose the underlying black paper. This print method has become popular because of its simplicity, in spite of the need of a special paper.

A closely related group to the thermal printers is the electrosensitive printers (Currah et al. 1948, Olivei 1972). In this case the electrical energy is directly used to make a chemical change of the coating of a specially treated paper to form the characters.

A perhaps more important group are the electrostatic printers, where the information to be printed is first formed by electrical charges which thereafter are developed by means of a carbon powder. To this group of printers belong the Xerox and Electrofax processes, where the electrostatic image is formed by means of light. The electrostatic image can also be formed by means of a large number of electrodes mounted across a moving paper (Stone et al. 1972, Sweet 1968).

Very similar to the electrostatic printing is the magnetic method (Brewster 1968). In this case a magnetic image is formed in a recording surface, which will be developed by a magnetic powder, and thereafter transferred to a paper.

By using light sensitive papers and a cathode ray tube to form the characters, very fast line printers have been built. However the high cost of the paper makes these printers uneconomical for normal applications.

By controlling the direction of ink jets, characters and other kind of information can be printed on plain paper. Both mechanical and

electrical methods have been used for the control of the jets. A review of the different ink jet printing methods is given by Kamp-hoefner (1972).

The print method investigated in this report belongs to the group of ink jet printers. Consequently a number of references to reports on this type of printing method are given in the reference list at the end of this report. The print method used here was developed by Hertz et al. (1967) and has been investigated for different applications, such as color copying (Månsson 1972), graphic computer outputs (Smeds 1973) and character printing (Ernbo 1973). In this report the usefulness of mechanically deflected ink jets, the intensity of which is modulated according to Hertz et al. (1968), will be investigated closer. The first part of this report will deal with the printing technique and its performance, while the second part will discuss some applications.

1.2. The basic principle of the modulation of an ink jet

The method of ink jet printing used in this report was developed at Lund Institute of Technology in 1966. The development work used the existing proven techniques of Elema-Siemens of how to produce ink and ink jet nozzles.

Hertz et al. (1967) showed that a line-formed fluid jet can be transformed into a spray of fine droplets by the application of an electrical field near the nozzle producing the jet. This phenomenon can be easily demonstrated in the following way. In fig. 1.1.a, a jet of ink J is produced by forcing ink under high pressure through the nozzle N. Directly after leaving the nozzle the ink jet traverses a ring-shaped electrode E, which is connected to the somewhat conductive ink in the tube leading to the nozzle.

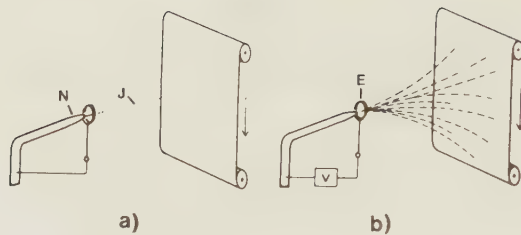


Figure 1.1. By forcing ink under high pressure through the fine nozzle N, an ink jet J is formed. This ink jet can be broken up into a spray of small droplets by applying a suitable voltage U to the control electrode E as shown in b).

If a voltage of sufficient magnitude is generated by the voltage source, it is found that the ink jet is transformed into a spray of fine droplets as shown in fig. 1.1.b. Since the ink jet is dispersed, obviously no recording trace is obtained on the paper during the time the voltage is maintained. Thus, by controlling the voltage of the electrode E in a suitable way the ink jet can be switched between the two modes, resulting in an on-off intensity modulation of the trace on the paper.

The phenomenon described here is explained by the fact that a fluid jet spontaneously breaks up into a train of drops shortly after leaving the nozzle (Lord Rayleigh 1879). If the electrode E is placed near this point of drop formation and an electric voltage of some hundreds of volts is applied to the electrode as shown in fig. 1.1.b, the tip of the jet will be charged, each drop carrying a charge of about 10^{-13} C. Since all charges are of the same type, they give rise to a strong repulsion between the drops which breaks up the jet into a spray a few millimeters from the point of drop formation as shown in fig. 1.1.b.

In the device shown in fig. 1.1.b, the ink spray still reaches the recording paper, thus generating a continuous background on the paper. Various methods to remove the spray were described by Hertz et al. (1967). One of these is shown in fig. 1.2.a, where a diaphragm D allows the undisturbed jet to pass while only a small

fraction of the spray can reach the paper through the hole in D. To remove the ink spray collected on the diaphragm D, this is made of porous ceramic material and connected to a suction pump. In the following this will be referred to as the "aperture method".

Another method, the so called "deflection field method", is shown in fig. 1.2.b. It is based upon the electrostatic charge of the droplets, which makes it possible to deflect them away from the jet axis by means of an electrostatic field transversal to their flight direction. Also in this case the deflected spray intercepted by the electrodes is removed by means of a suction pump.

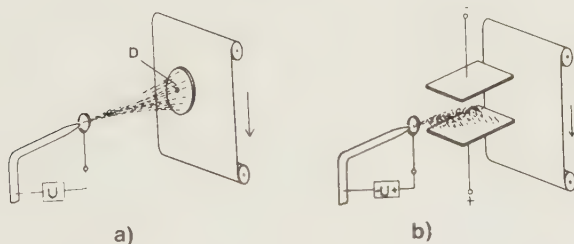


Figure 1.2. Removal of the spray by means of
a) aperture method
b) deflection field method

In the experiments made in this report nozzle diameters between 10 and 20 μm have been used. To generate a jet with an initial velocity of 20-40 m/s by means of the present nozzles, a pressure of about 20-50 atm has to be applied to the ink. To modulate such an ink jet a voltage of about 500 to 1000 V has to be used in the case of the aperture method, but a voltage of about 200 V is sufficient in the case of a deflection field.

By changing the form of the ring-shaped electrode to an oval, the jet nozzle can be mechanically deflected simultaneously with the intensity modulation. In the case of the aperture method to suppress the background the aperture has to be changed to a slit of

course. Using mechanical deflection together with a simultaneous electrical intensity modulation of the ink jet, characters can be printed as shown in fig. 1.3.

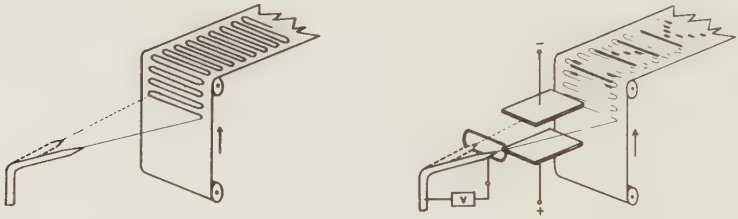


Figure 1.3. Printing by simultaneous mechanical deflection and electrical intensity modulation of the ink jet.

Since the nozzle can be oscillated at frequencies as high as 2 kHz and the upper frequency limit of the intensity modulation process is higher than 100 kHz (Månsson 1972), this method of printing ought to be interesting for many applications.

2. THE INTENSITY MODULATION OF THE INK JET

2.1. Introduction

In the previous chapter two different methods of preventing the spray of ink drops from reaching the paper were described. The first of these methods, the aperture method, uses an aperture in the form of a slit, when an oscillating ink jet nozzle is used. An advantage with this method is the simple electrode structure, but a higher control voltage, about 1 kV, is needed than in the case of the deflection method. This will have certain drawbacks such as high power dissipation in the amplifier feeding the control electrode and danger to personnel touching the electrode.

If a deflection field is used as described in the second method in chapter 1.2. a control voltage of about 200 V is sufficient. To limit the current to the high voltage electrode generating the deflection field a large resistance 10 M Ω can be connected between the voltage supply and the electrode. However, the more complicated electrode structure of the latter method increases the risk of break down between the electrodes caused by dust particles and ink drops.

Using the aperture method Månsson (1972) reported that a drop train has to contain about 5 drops to reach the paper. With the deflection field method and lower control voltage it is sufficient with one drop as can be seen in fig. 2.1.



Figure 2.1. Photograph of an ink jet with synchronized drop formation, where all but one drop is deflected.

The latter method will have a higher upper frequency limit and thus can be expected to produce higher resolution.

An inevitable drawback of the aperture method is that some drops of the spray will always reach the paper due to the stochastical distribution of the drops in the spray. Since it in many applications is necessary to let the print head stand still or move slowly relative to the paper, the aperture method may give rise to a general background, which is very undesirable. Thus the deflection field method should be used in these cases.

In preliminary experiments both methods have been used. However, the experiments described in this report have been made with the deflection field method only.

2.2. Electrode structure

Earlier it was mentioned that one of the drawbacks of using a transversal field to prevent the charged drops from reaching the paper was the more complicated structure of the electrodes. This in turn will increase the risk of electrical break down between the different parts of the electrode system.

To simplify the structure of the electrodes one of the electrodes generating the deflection field can be connected to the control electrode, as shown in fig. 2.2.

In this configuration the deflection field will vary, since the voltage of electrode F_2 is not constant but changes with the control voltage. However, since the typical control voltage V is about 200 V and the voltage of electrode F_1 is about 1200 V these changes of the field strength will have no harmful effect on the print out.

In the configuration shown in fig. 2.2.a, the power supply generating the deflection field can be floating and thus does not influence

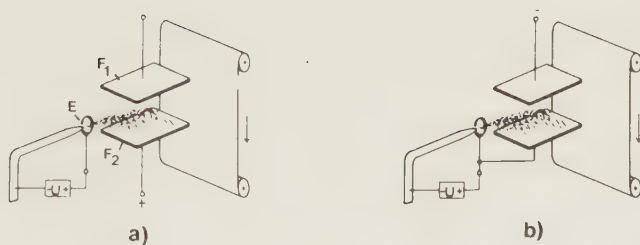


Figure 2.2. Different electrode configurations using a deflection field to prevent the charged drops from reaching the vapor:

- a) with a cloating voltage generating the deflection field
- b) simplified configuration.

the charging of the drops at the drop formation point. However, in the system, shown in fig. 2.2.b. the drop formation point has to be shielded from the high voltage electrode F_1 , otherwise the drops will always be charged. A small charge of the drops caused by the high voltage electrode F_1 can be accepted, since this will stabilize the jet by decreasing the tendency of the drops to merge along the jet axis due to a minor repulsion between the drops.

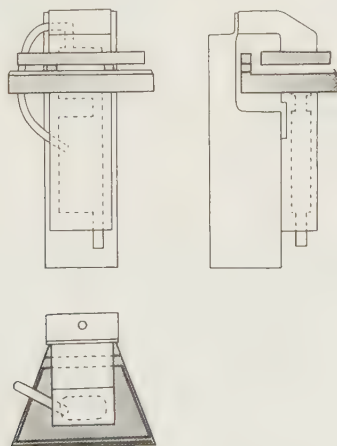


Figure 2.3. Electrode system designed to be mounted on a Mingograph galvanometer.

In fig. 2.3. a practical electrode configuration is shown, designed to be mounted on a Mingograph galvanometer which will be described in chapter 3.1.2.

Since the control electrode E and the lower electrode F_2 generating the transversal field shall be electrically connected, they are built as one part, thereby simplifying the mechanical mounting of the electrode system on the metal case of the galvanometer. Both the electrodes F_1 and E are made of a porous ceramic material that allows the removal of the deflected ink through two tubes by means of a suction pump. The tubes lead to the roof of a small container, to avoid electrical shortcircuiting of the electrodes through the tubes. Since the electrodes are made of non-conductive ceramics a layer of silver has been deposited on their surface to enable the connection of wires and ensure electrical conduction. This electrode system has been designed to be used at two different print head positions as shown in fig. 2.4.

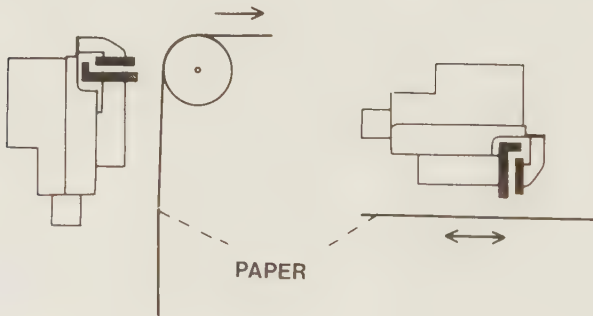


Figure 2.4. The electrode system, shown in fig. 2.3. mounted on a Mingograph galvanometer at two different positions of the print head.

Since it is possible to produce print widths up to 40 mm with this electrode system, it has been used for most of the tests shown in this report.

In some applications, e.g. typewriters (chapter 9), the preferable position of the print head is shown in fig. 2.5. In this way horizontal character lines can be printed on a vertical paper by either moving the print head or the paper.

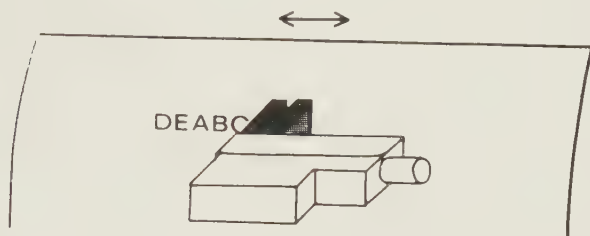


Figure 2.5. Position of the print head in the typewriter (chapter 9).

A special electrode system has been developed for this position of the print head. Since the electrodes were designed especially for a typewriter application, other aspects than merely the position of the print head have been taken into account. One of these is that the print head should not conceal the print out, so the supporting structure of the electrodes, shown in fig. 2.6., is placed on the underside of the print head.

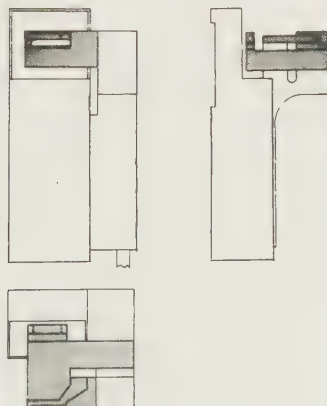


Figure 2.6. Electrode system of the print head position in fig. 2.5.

This is important in the typewriter application, where it is necessary to be able to read the last printed character.

In the opinion of the author, neither of the present electrode systems represents an ideal solution, since both of them show a double vacuum cleaner effect, caused by the high electrical field from electrode F_1 and the air stream from the suction pump. This effect will cause paper flock and other dust particles to be drawn inside the electrode system where they position themselves in the direction of the field and short circuit the electrodes. This effect can be decreased if the field from the high voltage electrode F_1 is shielded from the outside as indicated in fig. 2.7. However, the material of the electrodes presently in use is too brittle to allow the construction of structures as complicated as shown in the figure.

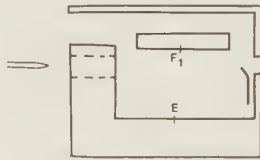


Figure 2.7. Shielding of the high voltage electrode F_1 .

Probably the removal of ink from the electrodes by suction can be entirely avoided in the case shown in fig. 2.5. if another material is used for electrodes and the deflected ink is removed by means of gravity as shown by Erikson and Månsson (1975).

2.3. Control voltage amplifier

In the introduction to this chapter it was mentioned that one of the drawbacks of the aperture method was the power dissipation in the control voltage amplifier in fig. 2.8., described by Ernbo (1973).

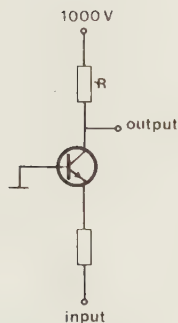


Figure 2.8. Control voltage amplifier with an output voltage of 1000 V.

If not too many drops shall receive an incorrect charge, the rise and fall time of the amplifier has to be less than half the time to create a drop. The rise time is mainly determined by the current available through the collector resistance to charge the capacitive load. Thus the rise time t_r will be:

$$t_r = 2.2 RC \quad (2.1)$$

Since the equivalent capacitive load is 60 pF a collector resistance as low as 3.8 k Ω is necessary to obtain a rise time of half the time to create a drop at a drop formation frequency of 1 MHz. This will cause a power dissipation of 260 W in the collector resistance when the output is low. In practice a collector resistance of 22 k Ω was used giving a rise time of 3 μ s and a power dissipation of 45 W.

If the transversal field method is used to remove the charged drops, control voltages less than 250 V are sufficient. For these voltages pnp-transistors are available, which makes it possible to construct amplifiers with much lower power consumption, as shown in fig. 2.9.a.

If the input signal is assumed to be 4 V as shown in fig. 2.9.b, then transistor T_1 will be turned on and thus connect the output to ground. When this input signal falls to 0 V instead, capacitor C_2

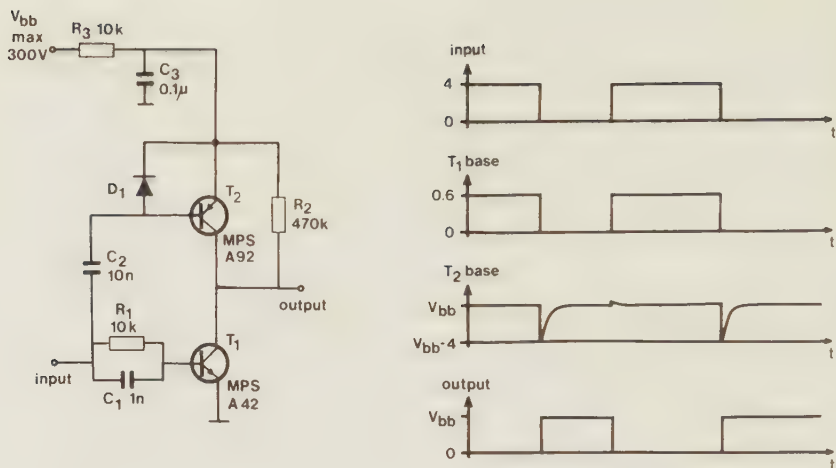


Figure 2.9. Control voltage amplifier with a maximum output voltage of 300 V.
a) circuit
b) signals

will be discharged through the base of transistor T_2 , which takes about 0.5 μs. During this time the transistor T_2 is conducting and the capacitive load at the output will be charged to V_{bb} . Resistance R_2 will now maintain the charge of the load if any leakage currents are present. When the input signal rises again to 4 V transistor T_1 will discharge the load and capacitor C_2 will be charged through diode D_1 . The network R_3C_3 is used to prevent any damage of transistor T_2 if the output is shorted to ground, or negative pulses shorter than 500 ns are applied at the input, in which case both transistors can be conducting.

The rise and fall time of the amplifier with a capacitive load of 60 pF is about 60 ns. The power consumption including the load is directly proportional to the switching frequency and has been measured to be 0.4 W at a frequency of 100 kHz.

3. THE OSCILLATING SYSTEM

3.1. The mechanical oscillation of the ink jet nozzle

3.1.1. Introduction

It has been shown above that characters can be printed with a single intensity modulated ink jet if the direction of that ink jet is changed in an oscillatory fashion. The oscillatory movement required for this is most conveniently obtained by mechanically oscillating the nozzle producing the jet. Suitable means to obtain such movements will be discussed in the present chapter.

In chapters 4 and 5 it is shown that the quality obtained by the present ink jet technology is dependent on the writing speed used, i.e. the speed with which the ink trace is generated on the paper by the jet. For the best results this writing speed should be in the range of 3 - 9 m/s.

If a sine wave is written on a paper by an oscillating jet nozzle as shown in fig. 1.3. the writing speed v_s is given by

$$v_s = \frac{A}{2} \omega \cos \omega t \quad (3.1)$$

A being the width of the scan and ω the frequency.

From this equation we find that for practical usable widths A of the trace, an upper frequency limit of about 1.5 kHz is sufficient for the oscillation of the ink jet nozzle, if a sine wave shape is used. As will be shown below, other shapes of the oscillations can be used, in which cases a larger bandwidth of the oscillatory system is required.

Since for the present investigations sinusoidal as well as other shapes of nozzle oscillations were required it was not convenient

to use a resonant system, e.g. a vibrating rod, to oscillate the nozzle. Therefore, a Mingograph ink jet galvanometer produced by Siemens-Elcoma, Stockholm, has been used in all of the experiments described in the present paper, since these galvanometers have a bandwidth from DC to about 1 kHz. Using these galvanometers practically all shapes of nozzle oscillation desired could be obtained within the frequency range required. Further, these galvanometers have the advantage of being able to generate a scan width A as large as 40 mm at practical nozzle/paper distances.

3.1.2. Principle of the Mingograph galvanometer

The ink jet producing part of the Mingograph galvanometer, shown in figure 3.1., consists of a thin glass tube with an outer diameter of about $100\text{ }\mu\text{m}$, fixed mounted in one end of the galvanometer housing. The other end is bent to 90 degrees and narrows to a nozzle producing the jet. On the tube a small permanent magnet, polarized along its diameter, is glued. The magnet is situated in a liquid damping system between the pole shoes of an electromagnet, the field of which thus will turn the magnet and by that deflect the nozzle. The necessary restoring moment of the magnet and nozzle is caused by the torsion, which the glass tube is exposed to when the magnet is turned in the alternating electromagnetical field.

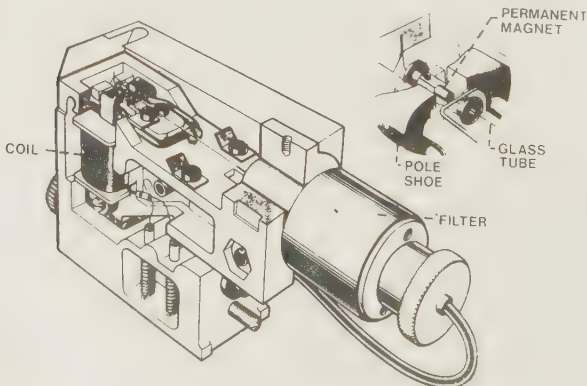


Figure 3.1. Mingograph galvanometer.

As the deflection angle is mainly proportional to the current through the coil of the electromagnet, the impedance of which is $17 + j\omega 0.06 \Omega$, these galvanometers have to be driven by a current generator.

3.1.3. Statical and dynamical errors of the Mingograph galvanometer

As the magnetical field from the coils is homogenous the statical deflection angle (Härtel et al. 1970) is given by (cf fig. 3.2):

$$\phi = I \cdot C \cdot \cos \phi \quad (3.2)$$

where I is the current in the coil and C is a constant (0.015 rad/ mA).

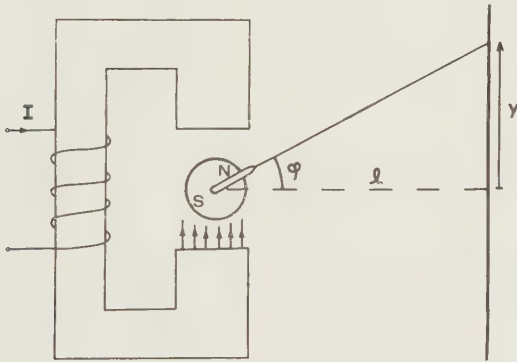


Figure 3.2. The statical deflection of the galvanometer.

The homogenous field causes an error E_1

$$E_1 = \frac{I \cdot \cos \phi - I \cdot C}{I \cdot C} \approx -\frac{\phi^2}{2!} + \frac{\phi^4}{4!} \quad (3.3)$$

Further it can be seen from figure 3.2. that the deflection y on the plane paper is

$$y = l \cdot \tan \phi \quad (3.4)$$

Hence y is not proportional to ϕ for large angles. The error E_2 caused by this is

$$E_2 = \frac{l \cdot \tan \phi - l}{l \cdot \phi} \approx \frac{\phi^2}{3} + \frac{2}{15} \phi^4 \quad (3.5)$$

In figure 3.3. the sum of the errors E_1 and E_2 is plotted. The deviation from the correct value is less than 10 % for all practical deflections and can thus be neglected in this application.

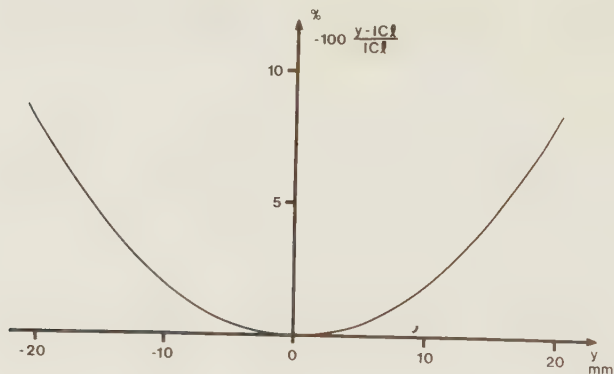


Figure 3.3. Deviation from correct deflection IC1 with a paper/nozzle distance of 30 mm.

In dynamical respects the deflection of the galvanometer nozzle can approximately be treated as a second order system with a transfer function:

$$G_O(s) = \frac{\phi(s)}{I(s)} = \frac{C \cdot \omega_0^2}{s^2 + 2\xi\omega_0 s + \omega_0^2} \quad (3.6)$$

where C is the statical sensitivity, ω_0 the undamped natural frequency and ξ the damping ratio. The natural frequency is given by the relationship:

$$\omega_0 = \sqrt{\frac{C}{J}} \quad (3.7)$$

where C is the torsional spring constant of the glass tube and I the inertia of the oscillating system. Further the relationship

$$\zeta = \frac{D}{2 \cdot \sqrt{I \cdot C}} \quad (3.8)$$

where D is the damping constant, is valid for the damping ratio.

Depending on the velocity $l_1 \cdot \dot{\phi}$ of the nozzle tip, the initial angle $\Theta(t)$ of the ink jet will not coincide with the deflection angle $\phi(t)$ of the nozzle, as shown in figure 3.4.

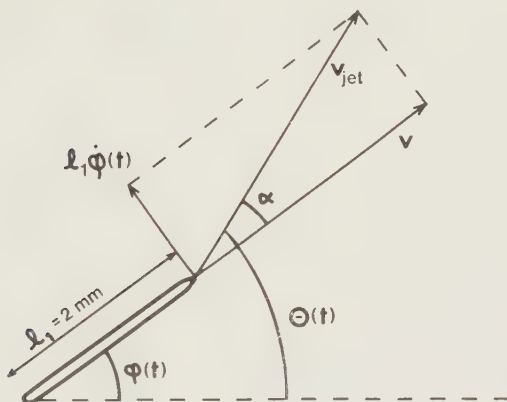


Figure 3.4. The initial angle of the ink jet.

Since the initial velocity v of the ink jet is about 40 m/s (Månsson 1971) the difference between $\Theta(t)$ and $\phi(t)$ will be:

$$\alpha = \arctan \left(\frac{\dot{\phi}(t) \cdot l_1}{v} \right) \cdot \dot{\phi}(t) \cdot 0.5 \cdot 10^{-4} \quad (3.9)$$

Thus the transfer function, giving the relationship between the initial angle of the ink jet and the current in the coil, can be expressed as:

$$\begin{aligned} G(s) = \frac{\Theta(s)}{I(s)} &= \frac{\phi(s) + \alpha(s)}{I(s)} = \frac{\phi(s)}{I(s)} (1 + 0.5 \cdot 10^{-4} s) = \\ &= \frac{(1 + 0.5 \cdot 10^{-4} s) \cdot A_0 \cdot \omega_0^2}{s^2 + 2\xi\omega_0^2 + \omega_0^2} \end{aligned} \quad (3.10)$$

In fig. 3.5. are shown the experimental results of the step response corresponding to $\frac{1}{s} G(s)$ as well as the amplitude function $|G(j\omega)|$. From this figure the following values can be obtained: $\omega_0 = 2 \pi \cdot 1000$ and $\xi = 0.5$.

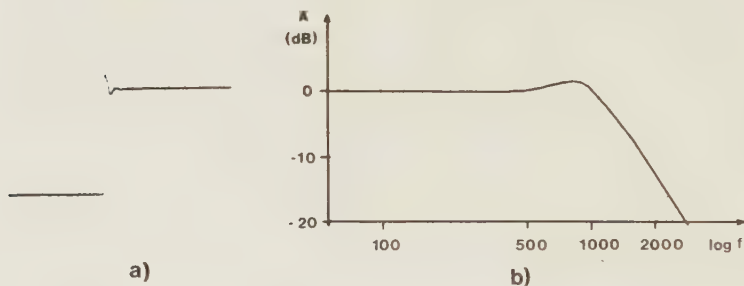


Figure 3.5. a) step response and
b) amplitude function of a Mingograph galvanometer.

The frequency response, shown in fig. 3.5. will be altered if a drop is allowed to grow up at the tip of the nozzle. If no special precautions are taken this happens easily if the ink supply is shut off. This drop will increase the inertia of the vibrating system, and thus decrease the natural frequency as well as the damping ratio, if it is not removed. The theoretical influence of the frequency response of drops of different sizes can be seen in fig. 3.6.

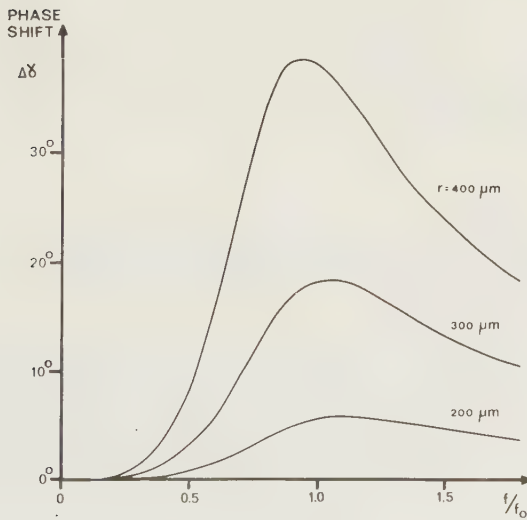
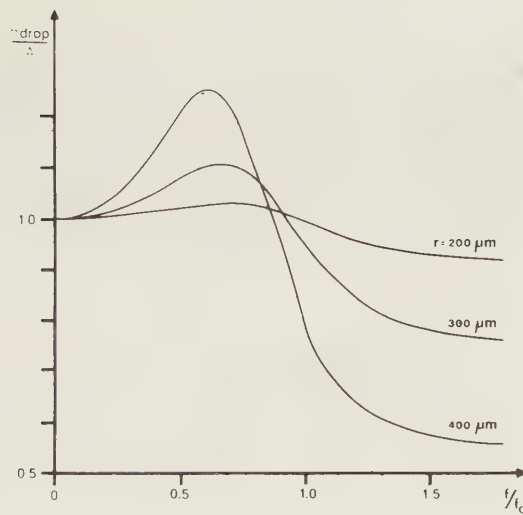


Figure 3.6. a) Relative changes of the amplitude response of the system due to different sized ink drops adhering to the nozzle.
b) Difference $\Delta\gamma$ of the phase delay between the electrical signal and nozzle movements due to ink drops adhering to the nozzle.

To remove the drop a porous material is situated closely to the nozzle (see fig. 3.7) in such a way that the drop is sucked into this material immediately upon its formation. Since the drop radius should not be larger than $200\text{ }\mu\text{m}$ (cf. fig. 3.5) the distance d in fig. 3.7 has to be of the order of $250\text{ }\mu\text{m}$ somewhat depending on the positioning of the galvanometer relative to gravity.

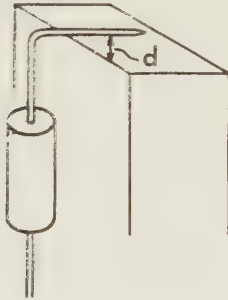


Figure 3.7. Drop remover.

3.2. The shape of the mechanical oscillation of the nozzle

3.2.1. Introduction

A sine wave shaped oscillation of the ink jet nozzle was indicated in fig. 1.3. showing the principle of the intensity modulated, oscillating ink jet. This oscillation mode is the easiest to implement mechanically, but has certain disadvantages.

Since the writing speed of the ink jet on the paper in the case of a sine wave motion varies as cosine of the deflection angle, a pulse of constant length on the modulation electrode will generate a bar on the paper, the length of which is a function of the deflection angle. Of course this could be circumvented by controlling the in-

formation transmission to the modulation electrode by means of a clock signal, the period time of which varies in a suitable manner to neutralize the influence of the speed variation of the nozzle deflection. As the mean frequency of the clock signal must be a multiple of the nozzle oscillation signal and phase locked to the mechanical oscillation, such a clock signal generator will increase the complexity of the electronics.

If the nozzle oscillation instead has the shape of a triangular wave, a clock signal with constant frequency could be used. However, a phase change between the clock signal and the mechanical oscillation is harmful also in this case as shown in fig. 3.8. By using only the rising or falling parts of the scan this problem can be avoided.



Figure 3.8. Dots on the same level (a) will disperse (b) if the phase between the mechanical oscillation and the clock signal changes.

As mentioned before and shown in chapters 4 and 5, the writing speed of the ink jet shall be low to optimize the resolution and density of the print out. Thus a sawtooth shaped oscillation ought to be most suitable, since, for a fixed frequency, this oscillation mode has the lowest possible writing speed.

However, the sawtooth scan requires a larger bandwidth of the mechanical oscillation system. Thus the shape of the scan has to be a compromise, depending on the application. Since most systems usable for oscillating the nozzle could be described as second order systems as a first approximation, a transfer function

$$G_O(s) = \frac{A_O \cdot \omega_O^2}{s^2 + 2\xi\omega_O s + \omega_O^2} \quad (3.11)$$

will be used for the oscillating system in this chapter, which will analyze more closely the different oscillating modes discussed above.

3.2.2. Sinewave shaped oscillation of the nozzle

The practical limit of the printing rate of an oscillating ink jet system is mainly determined by the frequency response of the oscillating system and the writing speed of the ink jet. The writing speed determines both the density and the resolution of the print out.

To achieve highest possible oscillation frequency, and thus maximum printing rate, with a given mechanical system a sinewave shaped oscillation has to be used. This shape of oscillation is also the easiest to produce, since in that case a resonance system can be used for the oscillation of the ink nozzle.

If the writing speed of a sinewave shaped scan shall not exceed 9 m/s, it can be deduced from eq (3.1) that the frequency must be lower than

$$f \leq \frac{9}{\pi \cdot A} \approx \frac{3}{A} \quad (3.12)$$

where A is the width of the scan in meters.

Since $A > 2$ mm for all practical purposes, the frequency response of the Mingograph galvanometer, shown in fig. 3.5, is sufficient if a sinewave shaped oscillation is used.

3.2.3. Triangular shaped oscillation of the nozzle

Since the writing speed of the jet in the case of an ideal triangular shaped oscillation is constant, this vibration mode has the advantage that constant time intervals represent bars of equal lengths on the paper. However, the required bandwidth of the vibration system is larger. The distortion of a triangular wave generated by a second order system with a damping ratio of 0.5 i.e. the Mingo-graph galvanometer, is shown in fig. 3.9, for different frequencies.



Figure 3.9. Distortion of a triangular wave generated by a second order system with a damping ratio of 0.5 for different ratios f/f_0 between the frequency f of the oscillation and the natural frequency f_0 of the system.

From figure 3.9. and especially figure 3.10. it can be seen that the maximum writing speed of the ink jet will always be less or equal in the case of a triangular shaped driving of the oscillating system to a sine wave shaped driving, and according to chapters 4 and 5 the resolution and density higher. Further, it is easier to generate a triangular wave than a sine wave with electronics, which is why triangular sweeps have always been used instead of sinewaves.

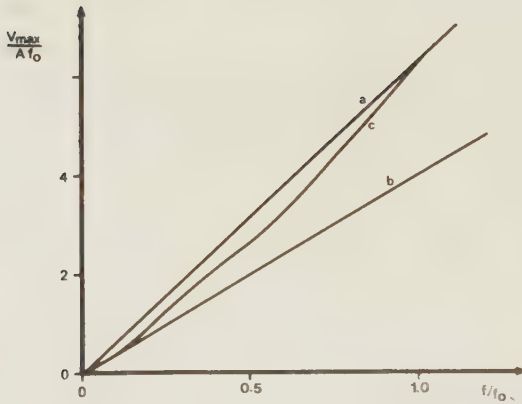


Figure 3.10. The maximum printing speed $v_{\max}$ of the ink jet relative to the paper divided by $A \cdot f_0$ for different ratios f/f_0

- a) Sine wave sweep
- b) Ideal triangular sweep
- c) Distorted triangular sweep by a second order system with a damping ratio of 0.5.

3.2.4. Sawtooth shaped oscillation of the nozzle

Using a sinewave or a triangular shaped oscillation the print out quality is rather sensitive to a change of the phase between the oscillation and the intensity modulation signal, if both directions of the scan are used as indicated in figure 3.8. Further, two adjacent scan lines are not parallel which decreases the quality of the characters. Especially the latter disadvantage can be circumvented by using only the rising parts of the oscillation. This implies that only 50% of the time is used for printing. Since, as mentioned before, the print quality is dependent on the writing speed, a sawtooth wave ought therefore to be a more suitable mode of oscillation for character printing. However, this oscillation mode demands an even larger bandwidth than the triangular shaped oscillation as can be seen from the frequency spectrums in fig. 3.11.

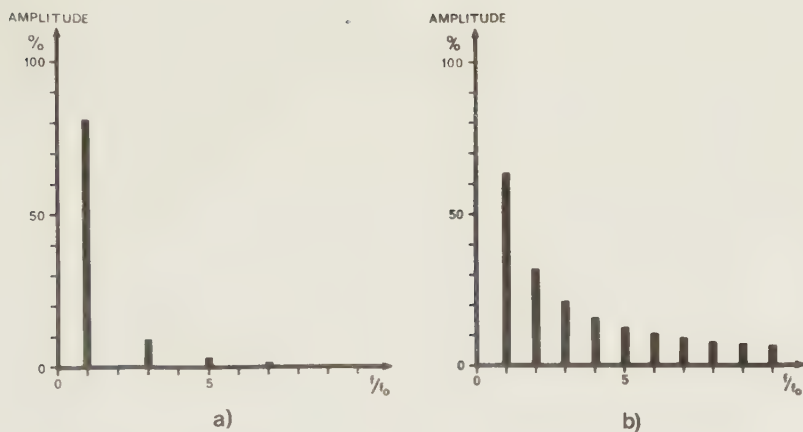


Figure 3.11. Frequency spectrum of
a) triangular wave
b) sawtooth wave.

To simplify the analysis the sawtooth oscillation can be considered as the difference of a ramp and a staircase signal as shown in fig. 3.12.

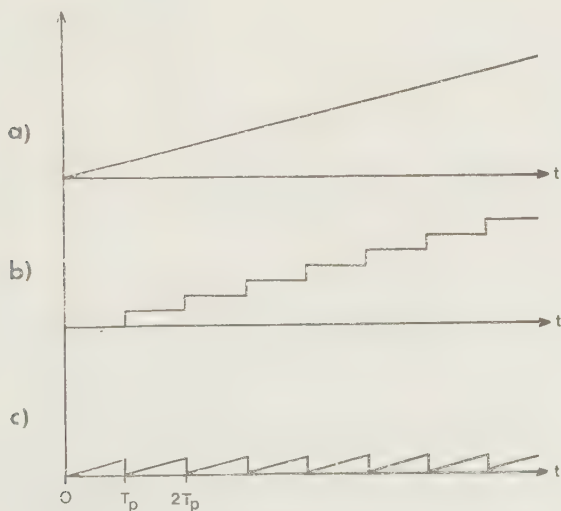


Figure 3.12. A sawtooth c) constructed as the difference of a ramp a) and staircase signal b).

The ramp $r(t)$ and staircase $c(t)$ signals can be denoted as:

$$r(t) = \begin{cases} 0 & t \leq 0 \\ t & t > 0 \end{cases} \quad (3.13)$$

$$c(t) = u(t - T_p) + u(t - T_p) \dots + u(t - nT_p)$$

where

$$u(t) = \begin{cases} 0 & t \leq 0 \\ 1 & t > 0 \end{cases} \quad (3.14)$$

The ramp and step response of a system with a transfer function $G_O(s)$ defined by eq 3.11 with a damping ratio of 0.5 are shown in fig. 3.13.

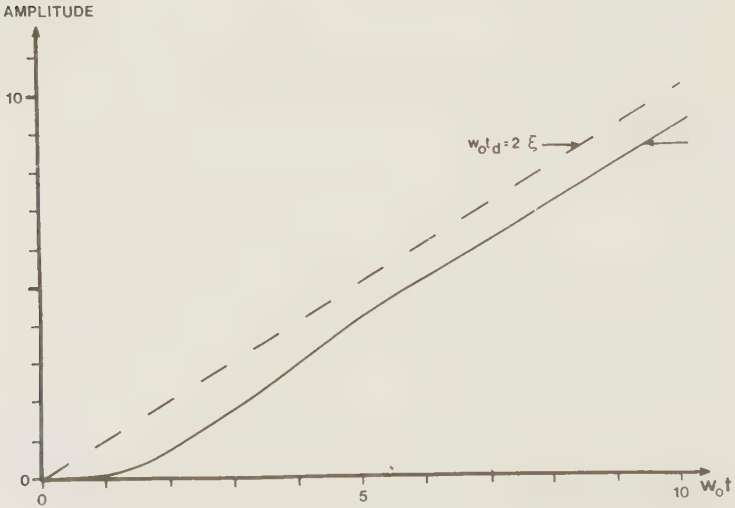


Figure 3.13. For text please see page 29.

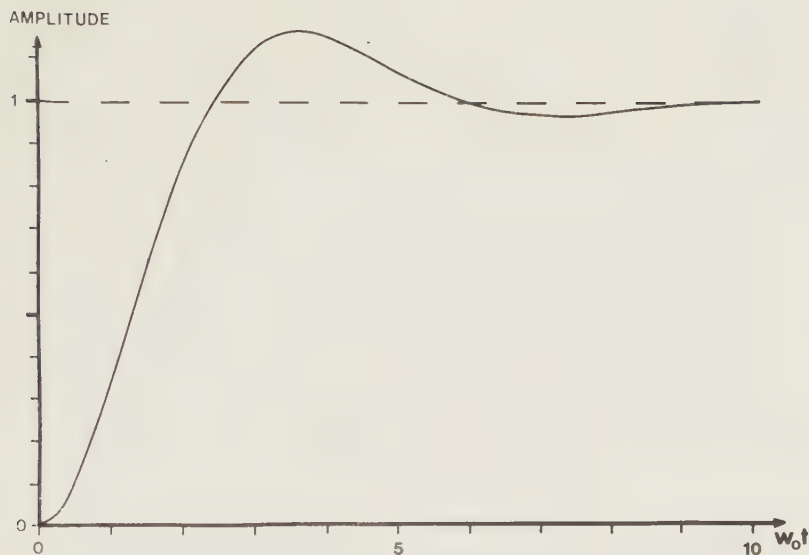


Figure 3.13. The response of a system with transfer function $G(s)$ when stimulated with a) a ramp t/T_0 and b) a step. T_0 and ω_0 are the natural period and frequency of the system respectively.

By this a sawtooth signal with amplitude A and a period time T_p can be expressed as:

$$i(t) = A \left(\frac{1}{T_p} \cdot r(t) - u(t-T_p) - u(t-2T_p) \dots - u(t-nT_p) \right).$$

with help of eq. (3.11) the deflection of the nozzle can be written as:

$$\phi(s) = G(s) I(s) = G(s) \cdot A \left\{ \frac{1}{T_p} R(s) - U(s)e^{-T_p s} - U(s)e^{-2T_p s} \dots \right\}$$

where the capital letters denote the Laplace transform of the small ones.

The output signal $G(t)$ shown in figure 3.14 of the system can thus be calculated as the difference of its ramp response, figure 3.13a and its step response figure 3.13b.

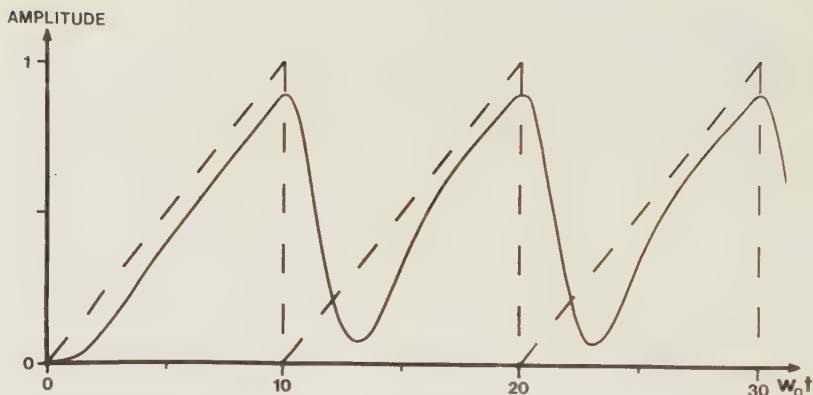


Figure 3.14. Distortion of a sawtooth signal by a second order system $G(s)$ with $\xi = 0.5$.

If the first period is neglected, the time during which the difference between the driving signal and the mechanical motion is not constant, is determined by the speed fluctuations caused by the steps of the input signal. If variations in the writing speed of 10% are accepted during printing the useful printing time T_{pp} can be calculated as follows. Figure 3.15 shows the deflection speed

$$\frac{d\phi(t)}{dt} = \mathcal{L}^{-1} \left\{ \frac{1}{s} G(s) \cdot U(s) \right\} \quad (3.17)$$

of the step response in figure 3.13b, equal to the impulse response of the oscillating system.

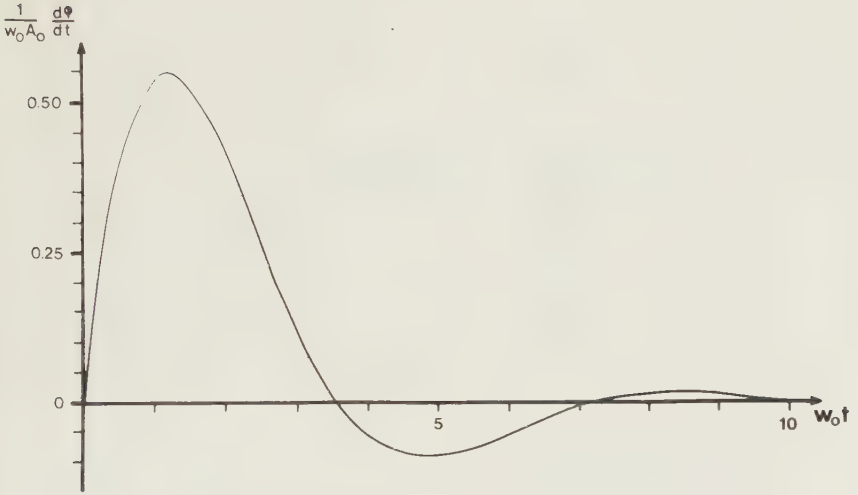


Figure 3.15. The deflection speed of the step response in fig. 3.13b.

Since the speed of the ramp is A/T_p , the point of time whereafter the speed caused by the step is less than $\pm 0.1 A/T_p$ can be seen from figure 3.15. In figure 3.16 is shown the ratio between the useful print time T_{pp} and the period time of oscillation T_p . Also shown in the figure is the width A_p of area usable for printing as a function of writing speed of the jet and frequency of oscillation. If a Mingograph galvanometer with a natural frequency of 1 kHz is used and the writing speed shall not exceed 8 m/s, then it can be seen from the figure that the highest possible frequency of a 3 mm wide print out is 510 Hz at a time ratio T_{pp}/T_p of 20%.

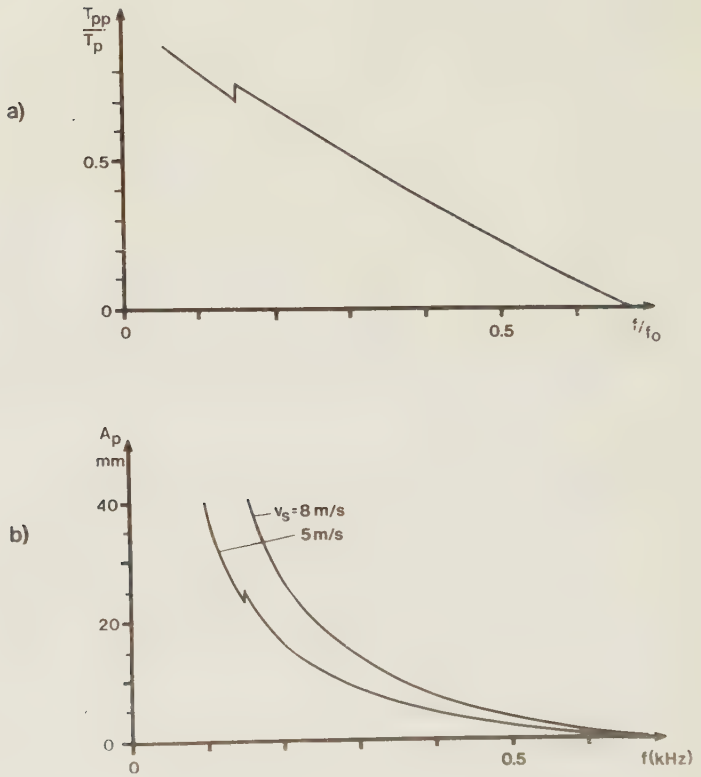


Figure 3.16. a) The ratio between the useful print time T_{pp} and the period time T_p of the oscillation, if T_{pp} a speed fluctuation of 10% during printing is accepted,

b) The corresponding width of the print out at different writing speeds v_s for a system having a resonance frequency f_0 of 1 kHz.

4. REFLECTION DENSITY

4.1. Introduction

Besides the resolution of the print out, another important factor, determining the print quality, is the reflection density. Due to the fact that the amount of ink carried by the jet per unit time is limited, the density will be low at high print rates. Further, the density varies in a stochastical way from point to point and thus gives rise to an annoying graininess (Månsson 1972).

The density is affected mainly by three factors, viz. the paper quality, the amount of ink deposited per unit area and the quality of the ink. In this chapter the influence on the reflection density of the two first mentioned parameters will be studied. It will be shown that the choice of the paper quality depends on the application, while the amount of ink constitutes a more fundamental limit of the present ink jet system. Thus in most applications it is not the resolution which determines the maximum print rate but the amount of ink deposited on the paper. Thus at high printing rates the density may be too weak, while the resolution is still acceptable.

4.2. Theoretical considerations

To allow theoretical analysis of the reflection density it is assumed in the following that the ink will not penetrate the paper but will form a layer of equal thickness on its surface, as shown in fig. 4.1. It is further assumed that the light will not be reflected at its entrance into the ink layer or give rise to any multiple reflections within the layer.

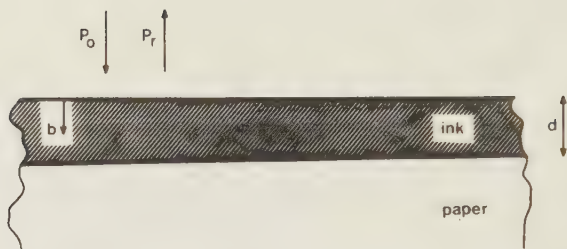


Figure 4.1. A cross-section of a printed area.

Under these assumptions, the intensity of the light entering the ink layer will decrease with the length of the path b , according to Beer's law (Ewing 1969) as:

$$P(b) = P_o 10^{-abc} \quad (4.1)$$

where a is the absorptivity and c the concentration of the dye of the ink solution. If the reflectance of the clean paper surface, viz. the ratio between the intensity of the incoming and outgoing light, is R_p , the intensity of the reflected light P_r of the sample can be written as (cf. fig. 4.1):

$$P_r = P_o 10^{-a2dc} R_p \quad (4.2)$$

However, if the ink is colored the above expression will only be valid at a given wavelength. Therefore equ. (4.2) has to be re-written in this case:

$$P_r(\lambda) = P_o(\lambda) \cdot 10^{-a(\lambda)2dc} \cdot R_p(\lambda) \quad (4.3)$$

Above radiometric quantities are used for the intensities and therefore are measured in energy units independent of wavelength. These can be transferred to photometric values (F), which are related to the sensitivity distribution of the human eye according to (Wright 1969):

$$F = K_m \int P(\lambda) \cdot V(\lambda) \cdot d\lambda \quad (4.4)$$

where F is the luminous flux, $V(\lambda)$ is the relative luminous efficiency and K_m is the luminous efficiency in lumens per watt off the monochromatic radiation ($\lambda = 555 \text{ nm}$) for which $V(\lambda)$ has its maximum value of 1.0.

By means of this equation (4.4), the luminous flux of the reflected light of a printed area can be expressed as:

$$F_r = K_m \int P(\lambda) \cdot V(\lambda) \cdot d\lambda = K_m \int P_o(\lambda) \cdot V(\lambda) \cdot 10^{-a(\lambda)2dc} \cdot R_p(\lambda) \cdot d\lambda \quad (4.5)$$

In the present case $P_o(\lambda)$ is assumed to be independent of λ (white light).

According to this, the reflectance R , defined as the ratio of the intensities of the outgoing and incoming light, will be:

$$R = \frac{F_r}{F_o} = \frac{\int V(\lambda) \cdot 10^{-a(\lambda)2dc} \cdot R_p(\lambda) \cdot d\lambda}{\int V(\lambda) \cdot d\lambda} \quad (4.6)$$

A more common measure is the reflection density D :

$$D = 10 \log \frac{F_o}{F_r} = 10 \log \frac{1}{R} \quad (4.7)$$

If the absorbtivity of the ink and the reflectance of the paper is independent of the wavelength, i.e., $a(\lambda) = a$ and $R_p(\lambda) = R_p$ this property will be designated as "grey" in the following. In that case relation (4.5) can be simplified and the density expressed as:

$$D = 10 \log \frac{1}{R} = 10 \log \frac{\int V(\lambda) \cdot d\lambda}{10^{-a_2 d c} \cdot R_p \cdot \int V(\lambda) \cdot d\lambda} =$$

$$= 2 a d c + D_p \quad (4.8)$$

where D_p is the reflection density of the paper ($10 \log 1/R_p$).

4.3. Measurements

From eq. (4.8) it can be seen that for a "grey" ink, the reflection density will be directly proportional to the thickness d of the theoretically assumed ink layer. Since this is not valid if $a(\lambda)$ is not independent of the wavelength it is clear that the shape of any curve describing the density of the print, e.g. the influence of the print rate on the density, will depend on the spectral response of the ink. Since it is difficult to produce a reliable black ink, a blue ink (Siemens-Elcoma EMT 123.400) has been used in almost all experiments reported here. In fig. 4.2 the absorptivity $a(\lambda)$ of this ink is shown. The ink used for this report has a dye concentration of 24 g/l. Thus any measurements of the density of samples made with this ink cannot be generalized and cannot be used to calculate the density of inks of another color.

This problem can be avoided if the density can be measured at a given wavelength only and not over the entire wavelength range of the human eye. However, the sensitivity of the densitometer used was not great enough to allow measurements of the density, if a filter having a narrow spectral bandwidth was used. This problem can be avoided in the following way. In section 4.2 a model is used in which the ink is assumed to form a continuous layer of constant thickness d on the surface of the paper which of course is a large simplification of the actual circumstances which exist when ink is deposited on a paper surface. However, to circumvent the difficulty outlined above and to arrive at results which can be

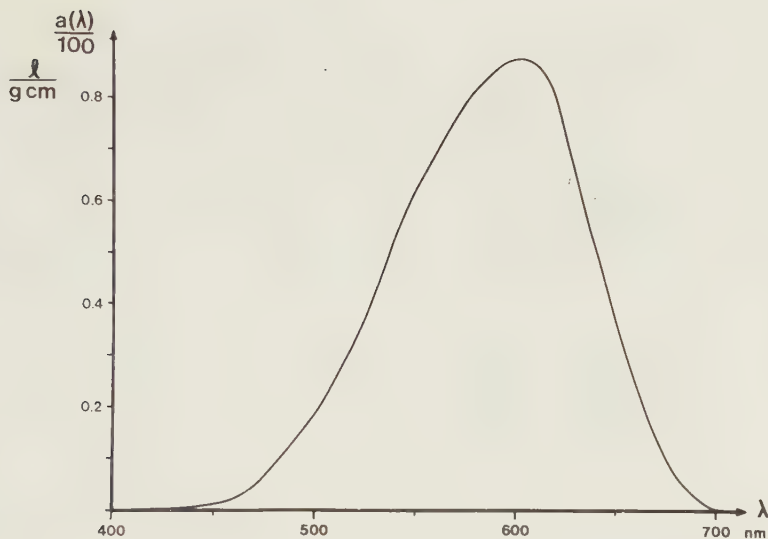


Figure 4.2. The absorptivity of the blue ink (Siemens-Elema EMT 123.400).

applied to inks of other wavelength dependence than the Siemens-Elema ink used here, this model is convenient.

Using this model we can define a thickness d_{eq} of an ideal ink layer which gives rise to the same reflection density as the actual print sample. Since the reflection density of the actual print samples are measured with a reflection densitometer, we have first to relate this thickness d_{eq} with the actual densitometer measurement.

Before explaining the procedure used to arrive at this dependence, the principle of the reflection densitometer (Mcbeth Quantalog RD219) used here for the density measurements is shown in fig. 4.3.

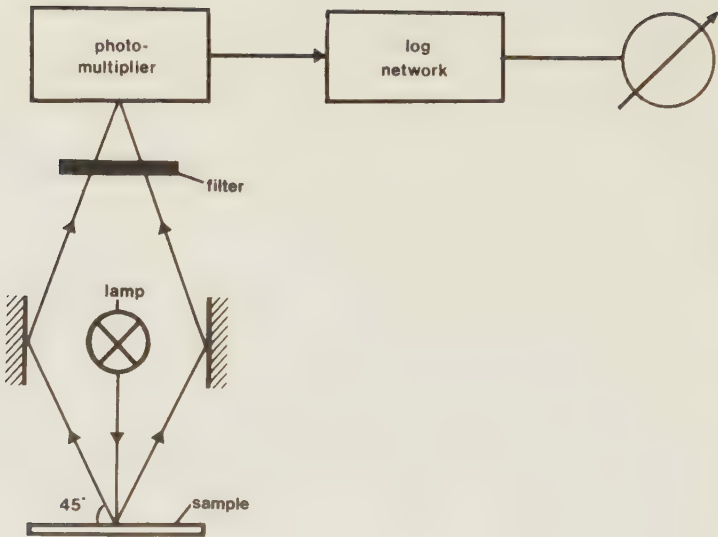


Figure 4.3. The principle of the reflection densitometer.

As can easily be seen the densitometer output signal D_m is

$$D_m = 10 \log \frac{\int E(\lambda) \cdot T(\lambda) \cdot S(\lambda) \cdot d\lambda}{\int E(\lambda) \cdot R(\lambda) \cdot S(\lambda) \cdot d\lambda} \quad (4.9)$$

$E(\lambda)$ = Emission of the lamp (Tungsten at 3854°K)

$R(\lambda)$ = Reflectance of the sample

$T(\lambda)$ = Transmission of the filter (Wratten 106)

$S(\lambda)$ = Sensitivity of the photomultiplier (RCA 931A)

The product $E(\lambda) \cdot T(\lambda) \cdot S(\lambda)$ is chosen in such a way that it is almost equal to the function $V(\lambda)$ defined in the previous section.

To find the dependence of the measured density D_m on the theoretically defined ink layer thickness d_{eq} , equation 4.9 can be used

if $R(\lambda)$ is known. However, using equation 4.2 we find for an ink which is wavelength dependent:

$$R(\lambda) = \frac{P_r(\lambda)}{P_o(\lambda)} = 10^{-2a(\lambda)cd_{eq}} \quad (4.10)$$

where $R(\lambda)$ is the reflection coefficient at the wavelength λ of an ink layer with a thickness d_{eq} deposited on a surface with a reflection coefficient $R_p = 1$ throughout the entire wavelength band.

Since $a(\lambda) \cdot c$ is known from fig. 4.2 the dependence of the reflection density D_m on the thickness d_{eq} can be found by numerical calculations using equation 4.9. The results of these calculations are shown in fig. 4.4.

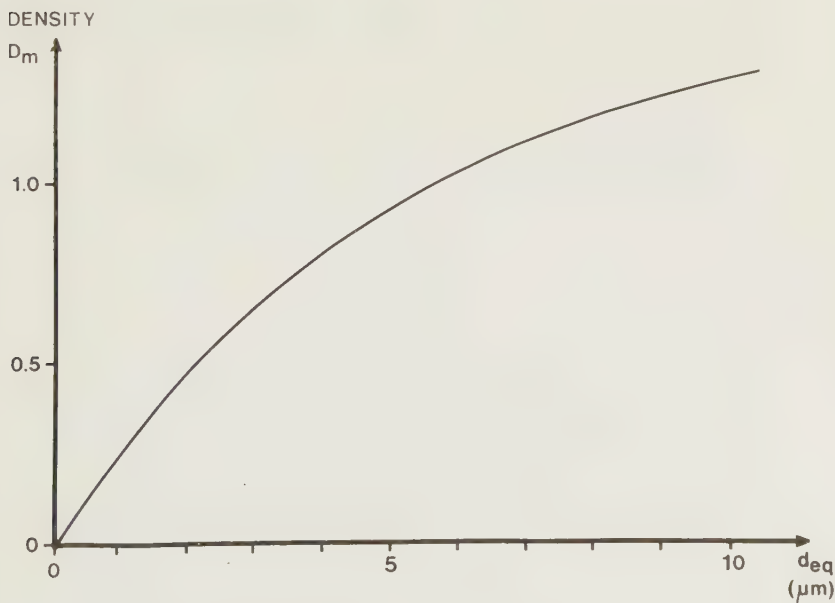


Figure 4.4. The theoretical dependence of the reflection density measured on the thickness d_{eq} of an idealized ink layer for the blue ink EMT (123.400).

In the measurements of the reflection density of different print samples the relation given in fig. 4.4 is used, i.e. all results are given in the equivalent thickness d_{eq} . Because of this the results given below can be used even if an ink of another color is used to predict the density by using equation 4.3. Of course the wavelength dependence $a(\lambda)$ of the new ink has to be known in this case.

This does not, however, apply to other than waterbased inks, since differences in surface tension and absorption in the actual paper would change the deposit of the ink on the paper surface, e.g. for an alcohol based ink.

The actual measurements to determine d_{eq} are made in the following way. Using the reflection densitometer described in fig. 4.3 the reflection density D_m of the sample is determined. Since the equivalent thickness d_{eq} obviously should be independent of the reflection losses on the paper surface, the reflection density D_p of the clean paper surface itself is measured. Thereafter the difference $D = D_m - D_p$ is used to find d_{eq} from fig. 4.4.

4.4. Density of non-overlapping ink traces

In section 4.2 the ink deposited on the paper was assumed to create a layer of constant thickness. However, if the oscillation frequency of the nozzle is too low compared with the speed of the paper, the ink traces on the paper will not overlap each other and thus give rise to a cross-section more like that shown in fig. 4.5. The uncovered parts of the paper between the ink traces will of course decrease the density of the print out.

To understand this situation more quantitatively we can make the following estimation of the reflection density. As earlier, we assume the ideal case, where the ink does not penetrate into the paper but forms a layer on top of it, the average thickness of which is d .

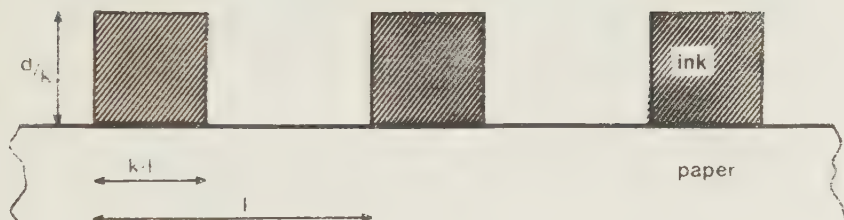


Figure 4.5. A cross section through a printed area where the ink traces are not overlapping.

If the absorptivity $a(\lambda)$ of the ink and the reflectance $R_p(\lambda)$ of the paper are assumed to be independent of the wavelength λ , the reflectance of the sample can be expressed as the sum of the light attenuated by the ink and the light reflected by the paper between the ink traces:

$$R = k \cdot R_p \cdot 10^{-2ad/k} + (1-k) \cdot R_p \quad (4.11)$$

where the meaning of k and l is described in fig. 4.5. From this we find for the density:

$$D = -\lg R = -\lg [k \cdot R_p \cdot 10^{-2ad/k} + (1-k) \cdot R_p] \quad (4.12)$$

By changing the frequency of the oscillation of the nozzle but keeping its amplitude and the paper speed constant, the number of ink traces per mm and by that the parameter k in eq. (4.12) can be altered. Since the area printed per unit time, determined by the amplitude of nozzle oscillation and the paper speed, is constant, the product ad ought to be constant too.

Thus the difference $D-D_p$ can be calculated for different values of k as is shown in fig. 4.6. Besides this, actual density measurements were made on special samples made for this purpose, the results of which are included in fig. 4.6. as small circles. As can be seen from the figure, the measurements agree well with the theoretical values.

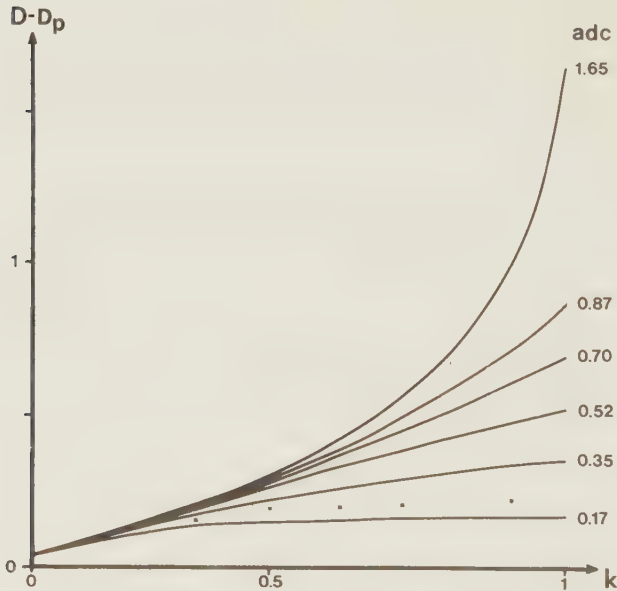


Figure 4.6. The influence of white areas between the scanning lines on the reflection density.

From fig. 4.6 it can be seen that the decrease of the density caused by the fact that the ink traces are not overlapping each other is especially pronounced at high densities. At low densities, the distribution of the ink on the paper is not of such importance in respect of density.

4.5. Results

To investigate the dependence of the reflection density on the printing rate, i.e. the scanned area per unit time, and the quality of the paper, print samples have been made with an oscillating nozzle without any intensity modulation using different print rates and papers. The oscillation frequency of the nozzle and the paper speed, determining the number of ink traces per mm in the moving direction of the paper, have been chosen in such a way that the ink traces are overlapping each other. Since the width of a single ink trace is about 0.1 - 0.2 mm, the oscillation frequency f_{osc} of the nozzle has to be:

$$f_{osc} > \frac{v_p}{2 \cdot 0.1 \cdot 10^{-3}} \quad (4.13)$$

where v_p is the paper speed, if blank areas between the ink traces shall be avoided.

A number of print samples, using different values of the frequency and amplitude of the nozzle oscillation and the paper speed, were prepared with eq. (4.13) in mind, on 6 different papers. The result of the density measurements, translated to equivalent thickness d_{eq} by the use of fig. 4.4 is plotted in fig. 4.7 against the inverted value of the area printed per unit time, $1/v_p \cdot A$, where v_p is the paper speed and A the width of the printed area.

Since the pressure used to produce the ink jet was constant (32 kg/cm^2) during the preparation of the samples in fig. 4.7, the volume of ink per second ($3.2 \cdot 10^{-9} \text{ m}^3/\text{s}$), Q , was also constant. Thus the thickness d_i of the ink layer if it is deposited on an ideal non-absorbing paper will be

$$d_i = \frac{Q}{v_p A} \quad (4.14)$$

which is represented in fig. 4.7 as a dotted line.

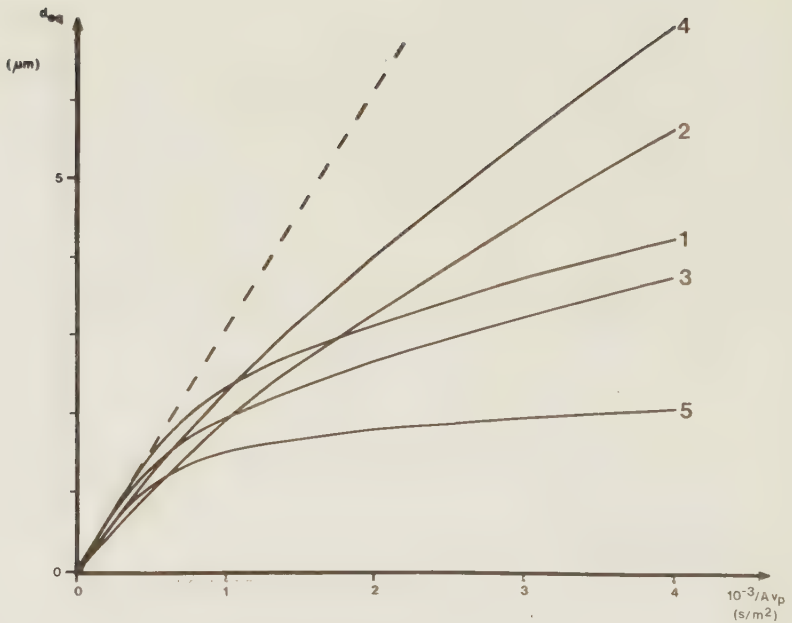


Figure 4.7. The dependence of d_{eq} on the printing rate for different paper qualities with a nozzle diameter of $15 \mu m$ and a pressure of 32 kg/cm^2 .

1. Offset paper a
2. Typewriter paper
3. Offset paper b
4. Baryte paper
5. Calculator paper

As can be seen from the figure, the baryte paper comes closest to this ideal line. This paper is normally used as a base material for light sensitive paper for photographic printing. Coated on the paper base is the baryte layer, an efficient diffuse reflector consisting mainly of barium sulfate powder suspended in gelatin. Apparently this layer prevents the ink from penetrating into the paper thus ensuring maximum light absorption.

In spite of the more ideal behaviour of the baryte paper, offset papers have a higher density at high print rates, i.e. small values of $1/V_p A$. This depends on the fact that, at high print rates, the scanning lines break up into dots and thus do not cover the scanned area completely. This effect will decrease the density as shown in equation (4.11) and fig. 4.6. Since the ink will disperse more in the coated offset papers than in the baryte paper, this effect will not be so pronounced when the offset papers are used and thus give rise to a higher density and a reduced graininess.

For special low speed and low quality applications calculator paper can be advantageous since the density will be almost constant for a large range of different values of $1/v_p A$. Further, the large amounts of ink per unit area, the printed area will dry more quickly, because most of the ink will be absorbed by the paper.

From the equation (4.13) it can be seen that the idealized thickness d_i of the ink layer can be made larger also by increasing the ejected volume Q . This can be achieved either by increasing the pressure producing the ink jet, and thus increasing the velocity of the jet or by using a nozzle with a larger diameter. However, there is a practical upper limit for both parameters. If the pressure is too high, above 50 kg/cm^2 for a $10 \mu\text{m}$ nozzle, the uncharged drops will produce a mist of yet smaller ink drops, when they hit the paper.

This is also valid if the nozzle diameter is increased and a pressure giving constant initial velocity of the ink jet is used. Fig. 4.8 shows the density of samples made on recorder paper and its dependence on the pressure P . At high print rates, and thus low densities, an increase of the pressure will improve the density of the print out greatly.

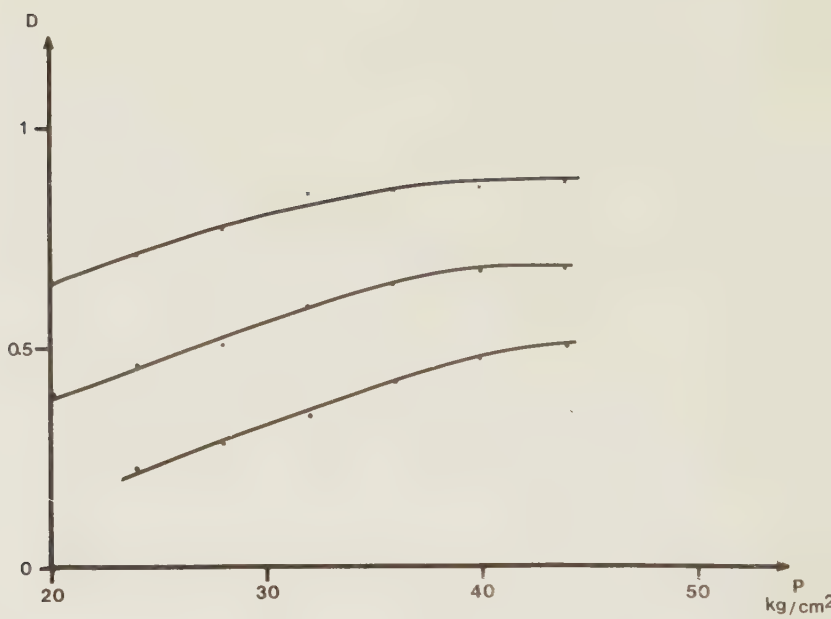


Figure 4.8. The dependence of the density on the pressure P for three different values of the product $v_p A$ (cf. fig. 4.7).

5. DEFINITION OBTAINABLE WITH AN OSCILLATING INK JET

5.1. Introduction

If this oscillating ink jet system shall be used for e.g. character printing, the maximum printing rate will not be limited by the upper frequency limit of the intensity modulation but by the definition and density of the print-out. The definition must be high enough to allow an adequate reproduction of the character matrix used.

In this chapter the influence of different factors on the definition will be discussed. These factors can be related to four main processes of the print system:

- a. the ink jet formation (e.g. the nozzle diameter, the initial velocity of the ink jet etc.)
- b. the mechanical deflection of the jet (e.g. writing speed of the jet relative to the paper, disturbances on the electrical signal driving the deflection of the nozzle)
- c. The intensity modulation (e.g. the electrode voltages, the shielding of the drop formation point from the electrode producing the transversal field)
- d. The stability of the uncharged jet. (This depends e.g. on the distance between the nozzle and the paper, air turbulence).
- e. The deposition of the drops on the paper (e.g. the quality of the paper, the amount of ink per unit area).

In this report the influences of the following factors will be discussed: the nozzle diameter, the initial velocity of the jet, the writing

speed of the jet, the modulation electrode voltage, the distance between the nozzle and the paper and the quality of the paper.

If nothing else is mentioned the following values of the parameters have been used for the experiments in this chapter:

Nozzle diameter	15 μm
Ink pressure	32 kg/cm^2
Modulation voltage	150 V
Nozzle/paper distance	28 mm
Paper quality	Mingograph recorder paper.

5.2. The measurements of the definition

Several methods have been proposed to measure the resolution and sharpness of an image. A summary of these methods and terms used in the photographic technology is given by Mees - James (1966).

Since the largest application field for the present oscillating ink jet system is in character printing, the sharpness is more important than the resolution, which is determined by how finely details can be printed. Therefore only the sharpness and not the resolution has been studied in this report.

Thus the acutance, introduced by Higgins and Jones (1952), was considered to be suitable to determine the definition of a print obtainable with an oscillating ink jet.

To calculate the acutance, print samples with a density step have to be prepared as shown in fig. 5.1.

These samples were scanned in a microdensitometer perpendicular to the direction of the paper movement indicated in fig. 5.1, as described by Månsson (1972) with an aperture in the form of a slit ($50 \times 3000 \mu\text{m}$). The result from such a measurement, fig. 5.2

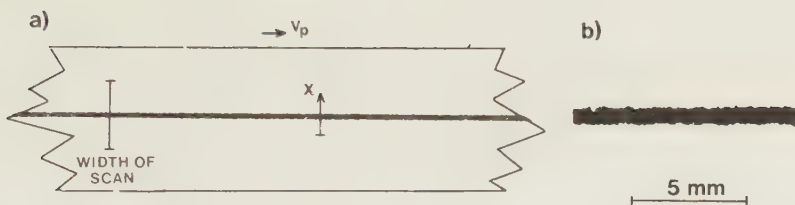


Figure 5.1. A print sample for determination of the acutance. The arrow v_p indicates the direction of the paper movement during printing while the jet scanned the paper perpendicular to this direction.
a) actual size
b) enlarged size

shows the intensity of the reflected light I_r as a function of the distance x on the sample.

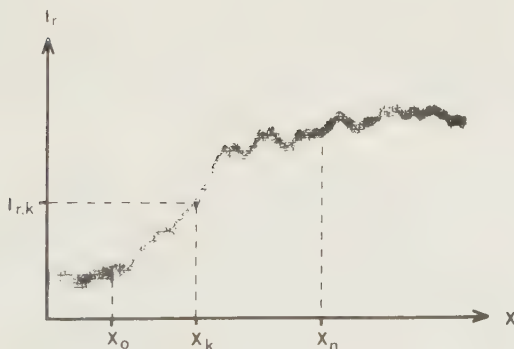


Figure 5.2. The distribution of the reflected light I_r of the sample in fig. 5.1.

If x_k are equidistant points along the scanning direction, then the acutance AC is defined as

$$Ac = \frac{\sum_{k=0}^n ((D_k - D_{k-1}) / (x_k - x_{k-1}))^2}{n \cdot (D_0 - D_n)} \quad (5.1)$$

where D_k is the density in the point x_k . Since the density is (cf. chapter 4):

$$D = \log \frac{1}{R} = 10 \log \frac{I_{in}}{I_r} \quad (5.2)$$

the acutance can be expressed as

$$Ac = \frac{\sum_{k=0}^n ((\log I_{r,k-1} - \log I_{r,k}) / (x_k - x_{k-1}))^2}{n(\log I_{r,n} - \log I_{r,0})} \quad (5.3)$$

Twenty points, i.e. $n = 20$, were used for the determination of the acutances. The measurements, including alignment of the slit in the microdensitometer with the edge of the print sample, and the computation of the acutance were very time consuming, because of which another method was used to measure the influence of different factors on the sharpness of the print out. This simplified method can be deduced in the following way.

If the print samples have an idealized density distribution as shown in fig. 5.3, corresponding to a distribution of the reflected light according to $I_r \sim 10^{-\text{konst} \cdot x}$ in the interval $x_0 < x < x_n$, then the definition of the acutance will be simplified to:

$$Ac = \frac{D_n - D_0}{(x_n - x_0)^2} \quad (5.4)$$

A good estimation of $D_n - D_0$ can be made by measuring with a normal densitometer the density difference between a printed and an unprinted area of the sample.

To get an estimation Δx of the distance $x_n - x_0$ a translucent scale was prepared photographically, which is shown in fig. 5.4. In this

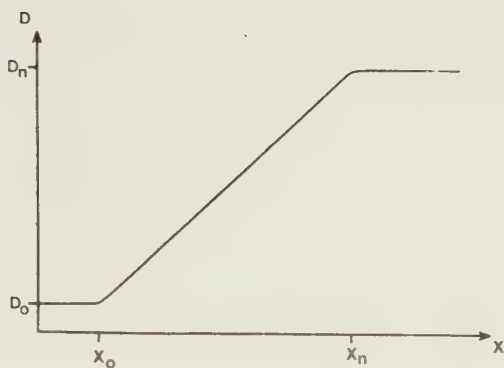


Figure 5.3. Idealized density distribution of a print sample, corresponding to a distribution of the reflected light according to $I_r \sim 10^{-\text{konst} \cdot x}$.

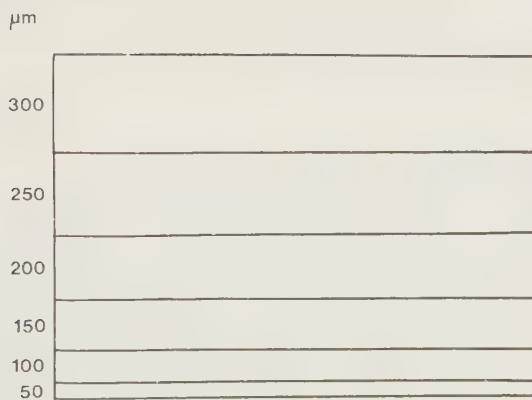


Figure 5.4. The scale for the measurements of Δx . The length of the scale was 10 mm.

scale the distance between the lines was increased with $50 \mu\text{m}$ for each line.

This scale was placed on the print sample and the distance Δx was measured by means of a microscope using a magnification of 25 to 40 times. The points where the density was about 10% and 90% of the density of a printed area were used as limits of the density transition. Since the determination of the limits is subjective, these measurements are not suitable for a comparison of the present print method with other print technologies. However, to get an estimate of the influence of different factors on the sharpness of the print out we think this method can be used. With the aid of these estimations of the density difference $D_n - D_o$ and the distance $X_n - X_o$, a value can be computed, which is reasonably close to the actual value of the acutance.

The acutance is dependent on the density and this in its turn is affected by the ink and the paper, which is more closely discussed in chapter 4. Thus, if the color of the ink or the concentration of the dye in the ink is changed, this will also alter the acutance. However, the distance Δx will normally not be affected by this. Therefore Δx has been used as a measure of the sharpness instead of the estimated value of the acutance.

5.3. Results

To make a comparison with other printing systems using other technologies possible, the acutance was measured with the microdensitometer for some print samples with equal density. To get equal density of the samples, the product of the paper speed v_p and the width of the scan A , i.e. the print rate, was held constant at a value of $19 \cdot 10^{-4} \text{ m}^2/\text{s}$. The result of these measurements plotted against the writing speed $v_s = 1/2 A \cdot$ are shown in fig. 5.5. The variations of v_s were achieved by changing v_p and A .

The influence of the writing speed, v_s , on the sharpness in these samples is also shown in fig. 5.6, where the estimated value Δx

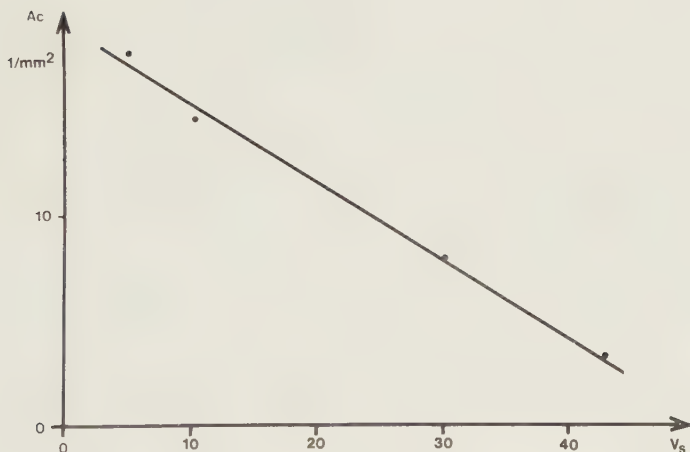


Figure 5.5. The acutance as a function of the writing speed v_s at a density of 0.92.

is plotted against v_s . No correlation between Δx and the amplitudes of the nozzle oscillation or the paper velocity was discovered. The distance between the points, where the density is 10 respectively 90 % of its final value can also be measured from the microdensitometer measurements. These results are shown in the diagram as crosses to give an idea of the correlation between the two different methods of measurements.

From figure 5.6 it is evident that the dependence of the writing speed v_s on Δx can be approximately represented by a straight line:

$$\Delta x = C_1 \cdot v_s + C_2 \quad (5.5)$$

where C_1 is 5.7 μs and C_2 100 μm .

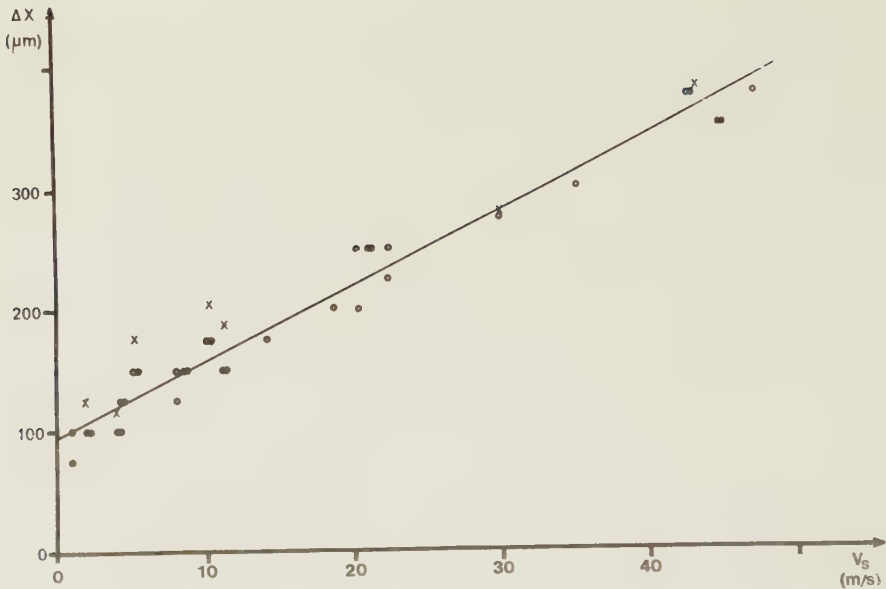


Figure 5.6. ΔX as a function of the writing speed v_s
x microdensitometer measurements.
o microscope measurements.

The decrease of the sharpness with v_s , i.e. the slope of the line, can be explained as follows. Since the mean time between the formation of two drops in this case is equal to about $2.2 \mu\text{s}$, the slope, $5.7 \mu\text{s}$, represents a time difference corresponding to three drops. Since no synchronization of the drop formation exists in this case, the slope can partly be explained by the phase differences between the drop formation and the voltage step applied to the control electrode. This phase difference will cause an uncertainty of the modulation of one drop at most. Further it should be observed that the drop merging at the ends of a drop train, described by Månsson (1972), is a random process.

A superficial comparison with the measurements by Månsson (1972) of the resolution obtainable with a stationary intensity modulated

jet, printing on the surface of a fast rotating drum, shows a higher value of the sharpness in the present measurements. Since the same type of intensity modulation of the jet was used in both cases, this is a somewhat surprising result. However, in Månsson's case the mean jet velocity has to be constant since otherwise the paper will reach different positions relative to the jet axis, while the drops travel from the charging point to the paper. When a system with an oscillating capillary is used, only changes in the direction and not the speed of the jet are important, since in this system the paper speed will always be low enough to be neglected.

The constant C_2 in equation (5.5) is mainly determined by the quality of the paper. It varies from 50 to about $150 \mu\text{m}$ which can be seen in fig. 5.7 where Δx is plotted against v_s for different paper qualities. The poor results of the offset paper are due to the fact that the ink diffuses into the coating of the paper.

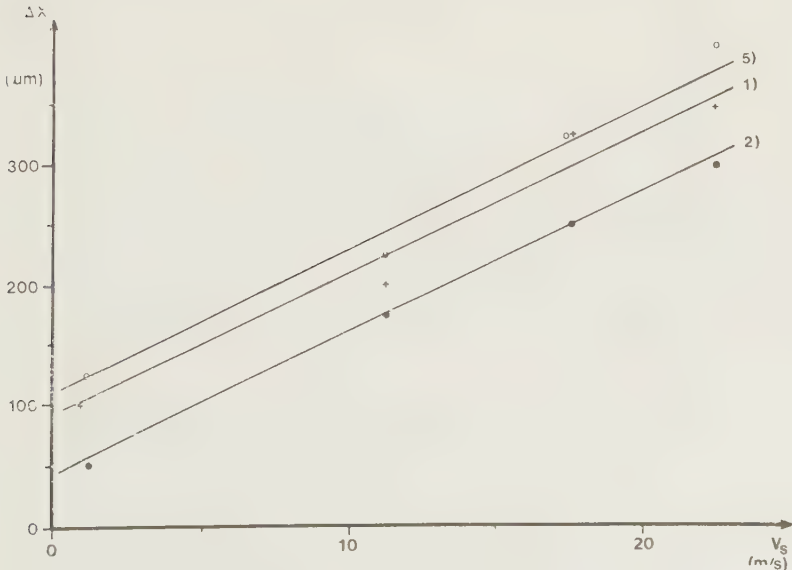


Figure 5.7. Δx versus the writing speed v_s for different paper qualities.
1. offset paper
2. typewriter paper
5. calculator paper

At writing speeds less than 1 m/s, the straight line dependence of Δx on v_s is not valid any more, since the amount of ink deposited on the paper will become too large. In that case the drops will hit an already wet surface, when they arrive at the paper and thus create new drops which will be deposited on the paper around the trace. This effect will increase Δx appreciably but this range of writing speeds was not considered to be of interest, consequently it has not been investigated further.

Earlier it was mentioned that the slope of the line representing the relationship between Δx and v_s , could be explained by a time uncertainty equal to about three drops. Since the drop formation frequency depends on the nozzle diameter, different nozzle diameters ought to change the slope of the line, which is shown in fig. 5.8.

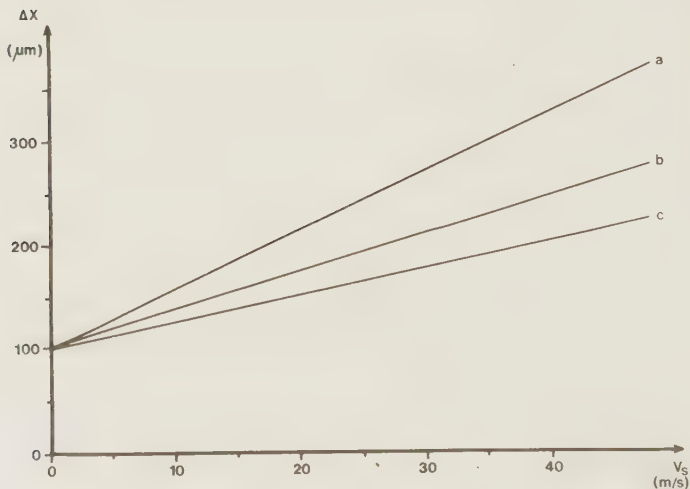


Figure 5.8. The influence of the nozzle diameter and the pressure

on Δx .

- a. $d_o = 15 \mu\text{m}$, $P_o = 32 \text{ kg/cm}^2$
- b. $d_o = 10 \mu\text{m}$, $P_o = 32 \text{ kg/cm}^2$
- c. $d_o = 10 \mu\text{m}$, $P_o = 40 \text{ kg/cm}^2$

The ratio between the slopes $C_1(15\text{ }\mu\text{m})/C_1(10\text{ }\mu\text{m})$ at a pressure of 32 kg/cm^2 is 1.53 which could be expected since the drop formation frequency f_d is given by (Rayleigh 1879),

$$f_d = \frac{v_o}{4.5 d_o} \quad (5.6)$$

and the initial jet velocity v_o is almost the same in the two cases.

The factor 4.5 is valid when spontaneous drop formation is used, but it can be decreased theoretically to π if the drop formation is controlled by means of mechanical oscillations generated for instance by a piezoelectric crystal, as described by Månsson (1972). This has, however, not been used, since in the case of an oscillating nozzle it is hard to mount the crystal close to the nozzle.

Further it can be seen from the figure that the expected influence according to (5.6) on Δx of the pressure, and thereby of the velocity v_o given by appendix I, is confirmed.

As mentioned in the introduction to this chapter, there are many other factors which affect the sharpness. If, for instance, the distance L between the nozzle and the paper is increased, then the merging between the drops observed by Månsson (1972) will be more pronounced. Thus the sharpness will be decreased, which is shown in fig. 5.9. Δx is plotted against the pressure in this figure, which gives a more accurate measurement, since the distance L cannot be varied more than 24 to 40 mm in the test apparatus.

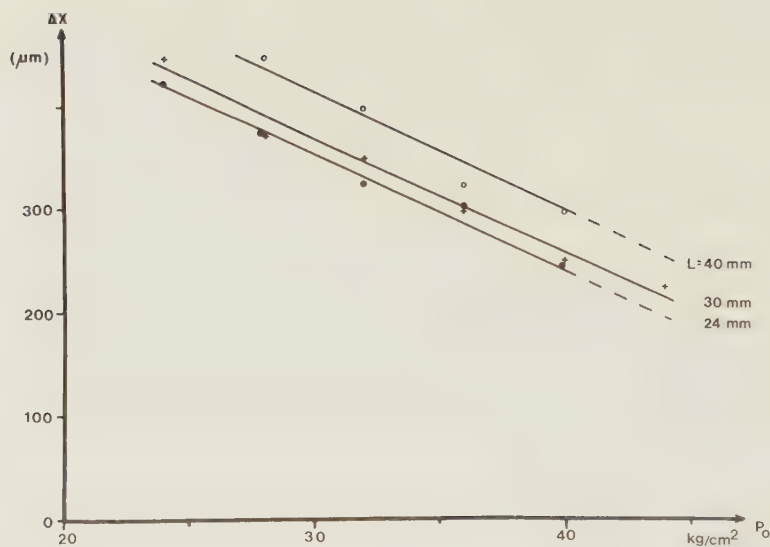


Figure 5.9. The influence of the distance L between the nozzle ($20\text{ }\mu\text{m}$) and the paper.

A slight influence of the charging voltage V_c on Δx at voltages less than 300 V can also be detected as shown in fig. 5.10.

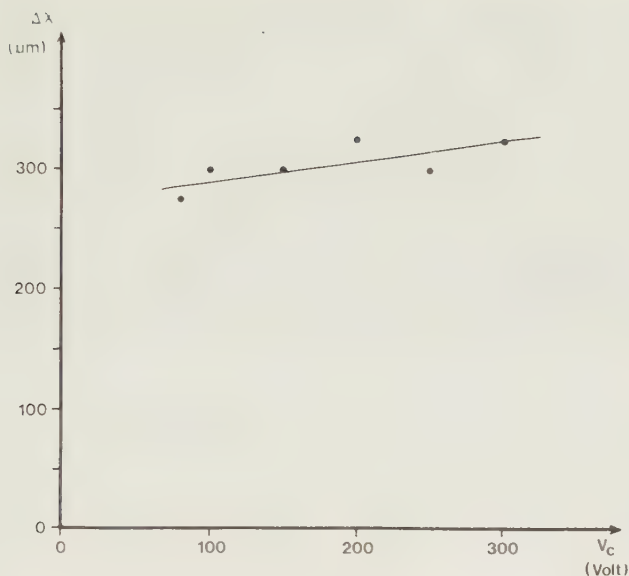


Figure 5.10. The influence of the charging voltage on Δx .

As a conclusion of this chapter it can be said that high sharpness can be obtained if the writing speed v_s , the nozzle diameter d_o , the distance L between the nozzle and the paper and the charging voltage V are small while the driving pressure of the ink and the paper quality are as high as possible. Because of other limitations of the system, a compromise usually has to be made when choosing these parameters for an actual printing system.

6. APPLICATIONS

6.1. Introduction

The ink jet printing method used in this report was originally described by Hertz et al. (1967). In 1972 a more extensive investigation of this method was published by Månsson (1972). At that time the so called "aperture method" (cf. 1.2) was used to achieve the intensity modulation. This method allows a continuous modulation of the density on the paper. Månsson investigated the possibility of using three non-oscillating ink jets of different colours to make a colour copying apparatus. In his apparatus both the original and the paper were fastened on a fast rotating drum as in most facsimile transmission equipments. However, among other difficulties the stability of the continuous intensity modulation as well as the scanning device was hard to control.

Smeds (1973) avoided some of these problems by using the so called "deflection field method" (cf. 1.2) for an on-off modulation of the ink trace. Instead of copying an original a computer was used to generate the pictures to be printed. In this way Smeds developed a colour plotter intended as a computer output device.

If an oscillating ink jet is used, pictures can be printed on a recorder which has the advantage that a continuous paper web can be used. So far, oscillating ink jet nozzles have been used for the generation of black and white pictures only. Examples of this is the print out of ultrasonic echocardiograms (UCG) of the heart in real time as shown by Erikson & Gudmundsson (1970) and Lindström et al. (1973). A sample of such a print out is shown in fig. 6.1. in natural size.

Due to the fact that the deflection angle of the ink jet nozzle is limited, a print out wider than 40 mm (cf. 3.12) cannot be achieved with one nozzle. If a larger width of the print out is desired, a

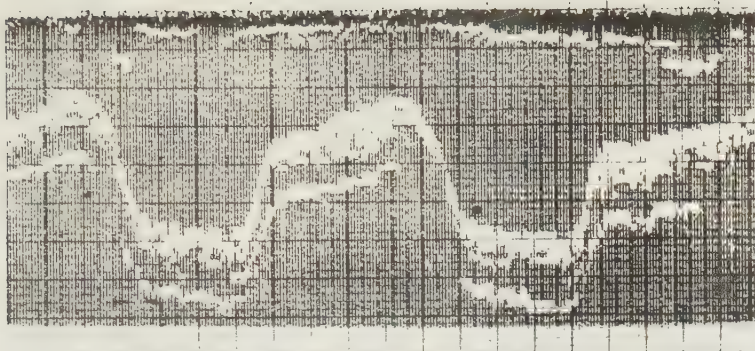


Figure 6.1. Print sample of ultrasonic echocardiograms made by one oscillating ink jet. (paper speed: 50 mm/s, nozzle diameter 10 μ m).

number of oscillating nozzles can be mounted side by side. In this way the complete print out consists of a number of 40 mm wide strips.

A later version of the UCG recorder used two nozzles to produce an 80 mm wide print out. Due to the similarity between the videosignal of the ultrasonic reflectoscope and television transmission, this apparatus can also be used to print out TV pictures. In fig. 6.2 a print out obtained with this system is shown where the upper and lower parts of the picture are printed by two separate oscillating jets.

The advantage of using oscillating instead of non-oscillating ink jet nozzles is that in the case of oscillating nozzles a continuous paper web can be used for the print out, while in the case of non-oscillating nozzles a sheet of paper has to be attached to a rotating drum.

The applications mentioned above all lie in the field of picture ge-



Figure 6.2. Print out of a TV picture obtained by two on-off modulated ink jets, one for the upper half (A) and one for the lower half (B) of the picture. (Time to produce one picture about 3 seconds).

neration. However, ink jets can also be used to print alphanumeric characters (Ernbo 1973). Since the ink jet modulation system is very fast, the application of this method to line printers has been discussed. To make maximum use of the modulation speed, non-oscillating nozzles were investigated. Ernbo (1973) showed that this system was able to print about 800 lines/s. However, to be able to print 80 5 x 7 matrix characters per line, 400 nozzles, one for each column of the 80 characters, are required in a line printer. With the present technology the nozzles cannot be mounted closer to each other than 10 mm, because of which the construction of a complete 80 ch/line printer seems to be rather complicated.

However, a system where the paper moves parallel, instead of perpendicular, to the text lines, has been developed recently (Erikson & Månsson 1975). Due to the direction of the paper movement, only one fixed nozzle for each matrix row of each text line is required instead. This system is capable of printing 4 lines of 7×9 matrix characters at a paper speed of 3 m/s using $9 \times 4 = 36$ jets and is mainly intended for the addressing of letters at high speed.

It is shown in the present paper (cf. chapter 1.2) that such a printer can be constructed much more easily by using only one oscillating jet, the direction of oscillation being perpendicular to the paper movement. Such a printer allows the printing of one line (cf. chapter 7) up to six lines (cf. chapter 8) simultaneously. The use of one ink jet only, of course, causes a decrease in printing speed, thus a six line single jet printer is about 50 times slower than the multiple fixed jet printer mentioned above (Erikson & Månsson 1975).

If only numbers are to be printed, even an oscillating ink jet can be used up to a paper speed of 2.5 m/s. This has been shown by Erikson (1974) who built such a printer to print certain numerical information on betting coupons. Since this was required only for control purposes, the only requirement made on character quality was that they should be recognizable. In this application the fact that ink jet printing is a non-impact process was also very important because of the high speed at which the coupons were moving at the printing station. This advantage of the ink jet printing should be of great value even in other applications, e.g. the marking of packages etc.

An application where another advantage of ink jet printing, namely its noise-free operation, will be apparent is an ink jet typewriter. Since in this case paper speeds, relative to the print head, of some meters per second are not of interest, an oscillating ink jet nozzle ought to be most suitable. In chapter 9 an ink jet typewriter is described, which is capable of printing 50×9 matrix charac-

ters per second. To make use of this high print rate, the typewriter is designed mainly as a computer terminal or teletype printer.

7. A TESTING APPARATUS

... Introduction

For the testing of different nozzle diameters, electrode systems, character matrices etc. a special apparatus, shown in fig. 7.1, has been constructed. The apparatus contains a printing head, a paper transport and electronic circuitry to generate necessary electrical signals for character generation as well as control circuits for paper speed control.

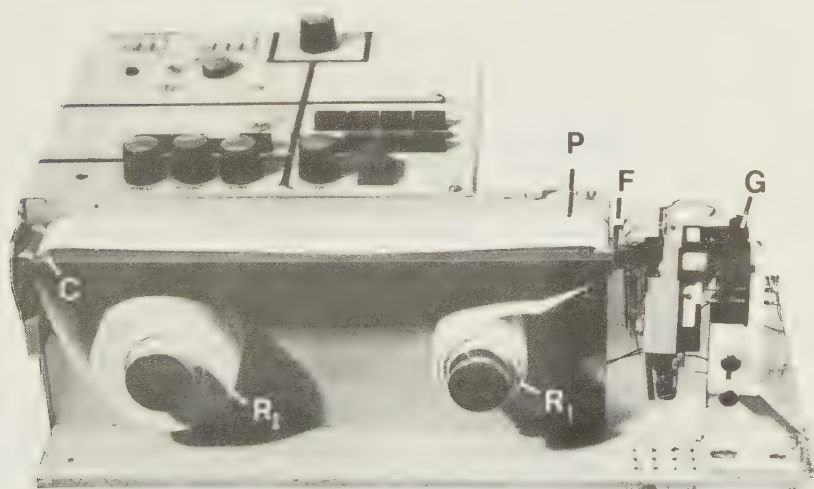


Figure 7.1. Apparatus for experiments.

In the figure a print head using an ink jet, galvanometer G (cf. 3.12) and electrodes E are mounted in front of the paper drive. The paper P is transported in front of the print head from supply reel R_1 by means of the capstan wheel C, whereafter it can be rewound on reel R_2 with a constant moment.

The control panel, shown in fig. 7.2, is divided into three parts, i.e. paper transport speed control P_1 , nozzle oscillation control P_2 , and intensity modulation signal control P_3 .

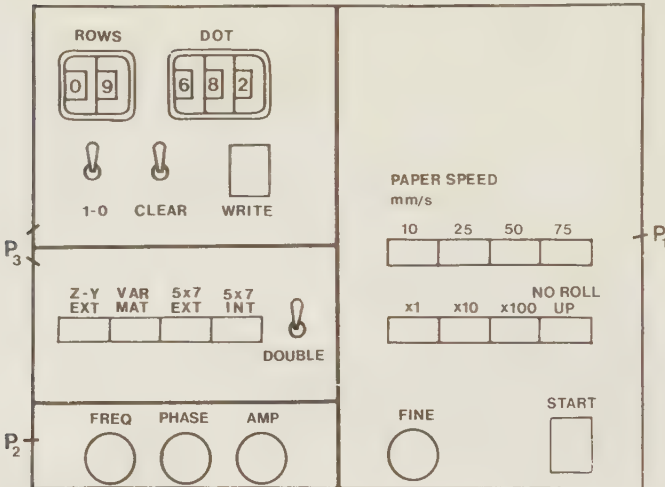


Figure 7.2. The control panel.

The apparatus includes two different character generators; one using a ROM containing 64 different 5×7 matrix characters and another one which allows for a matrix having a variable size. The latter character generator makes use of a 1024 bit shift register which has to be programmed for each experiment.

The character generators, the nozzle oscillation control and the paper transport servo will be described more closely in the next sections of this chapter, while the last section will describe some results of experiments made with this device.

7.2. Paper transport

The paper transport, partly visible in fig. 7.1, uses two DC-motors to move the paper in front of the print head; one driving the capstan and another one for the take up reel.

The capstan motor M1 and thus the paper velocity is controlled by a servo system, the circuit diagram of which is shown in fig. 7.3. To measure the speed of the capstan motor, a DC-generator G is connected to its axis, the output voltage of which is compared with a reference voltage by means of an operational amplifier. The paper velocity, properly the reference voltage, can be set between 10 mm/s and 5 m/s by switches on the control panel P₁ shown in fig. 7.2.

To wind up the paper on the take up reel with constant moment, motor M2 is controlled by a current generator.

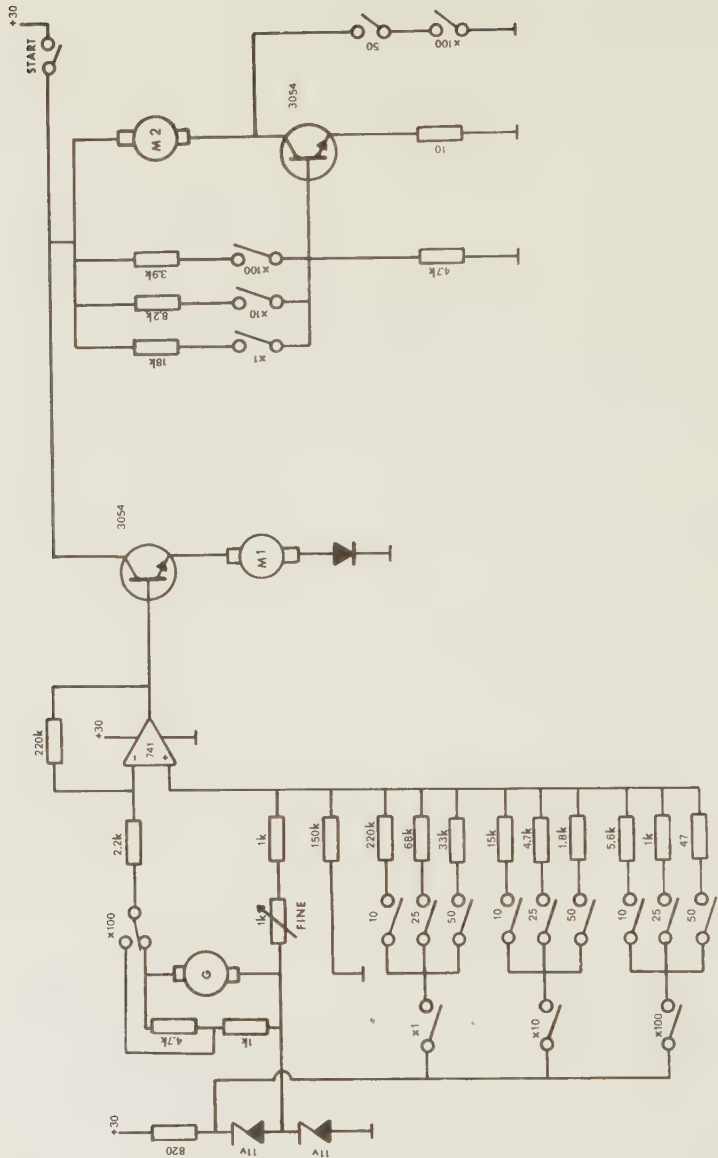


Figure 7.3. Servo system of the paper transport.

7.3. Nozzle oscillation control and system clock

A triangular signal is used in this device to control the nozzle oscillation, because this wave type is easily generated and phase-shifted by means of electronics. A sawtooth signal did not seem to be practical for general tests, since this wave type cannot be used to oscillate the nozzle of an ink jet galvanometer correctly at higher frequencies because of the limited bandwidth of the galvanometer.

To ensure synchronization of the nozzle oscillation with the signal controlling the intensity modulation of the ink jet, a signal SYNC is received from the character generator used as shown in fig. 7.4.

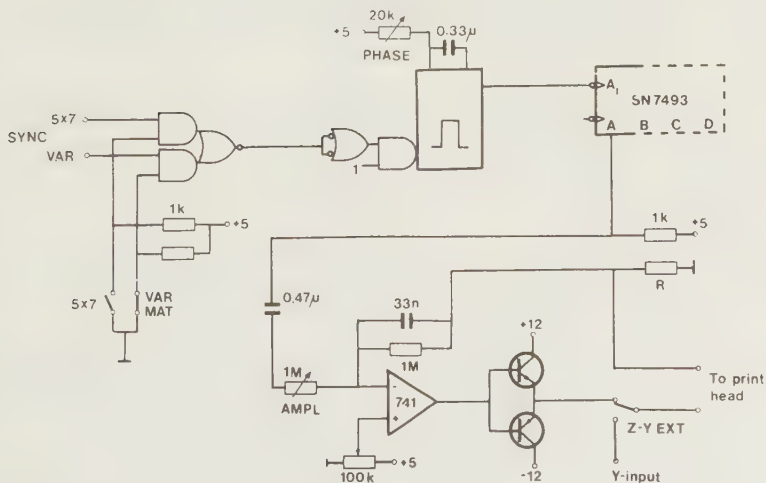


Figure 7.4. Nozzle oscillation control.

The falling edge of this signal, occurring each time the nozzle shall change direction of oscillation, is delayed by means of a one-shot, the pulse length of which can be changed to achieve a variable phase shift.

Thereafter the signal is divided to a symmetrical square wave of half the frequency of the incoming signal by means of a flip-flop included in the counter SN7493, the remainder of which is used for other purposes.

The triangular signal is generated by integrating the symmetrical square wave by means of an operational amplifier. Since most of the systems for oscillating the nozzle make use of magnetical forces and therefore include inductive coils, the signal to the oscillating system has to be driven by a current generator. This is achieved by a feedback voltage generated across the resistor R, which is proportional to the current through the driving coil of the nozzle oscillation system. This feedback voltage is applied to the integrator circuit.

The system clock, shown in fig. 7.5, consists of two series-coupled one-shots, the first of which has a variable pulse length to allow changes of the print out rate.

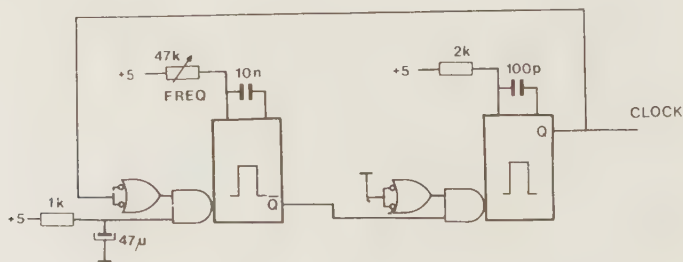


Figure 7.5. System clock.

7.4. 5 x 7 matrix character generator

The information for the 64 character matrices is stored in a Read Only Memory (ROM). This ROM has two address inputs: one for the ASCII (American Standard Code for Information Interchange) code of the selected character while the other inputs determine the column of the said character which is to be connected to the seven outputs of the ROM.

By means of a multiplexer, shown in fig. 7.6, the matrix row counter controlled by the system clock scans the seven outputs of the ROM. The row counter also controls the nozzle oscillation.

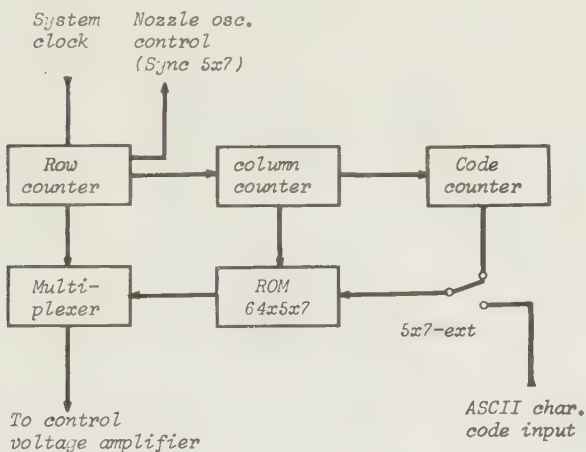


Figure 7.6. Block diagram of the 5 x 7 matrix character generator.

Each time the nozzle has completed a period of oscillation the column counter is increased by one step and thereby connects the next column to the outputs of the ROM. The character codes can either be obtained from an external source or from an internal code

counter, which is increased by one step each time a character is printed. In this way all characters stored in the ROM are printed serially.

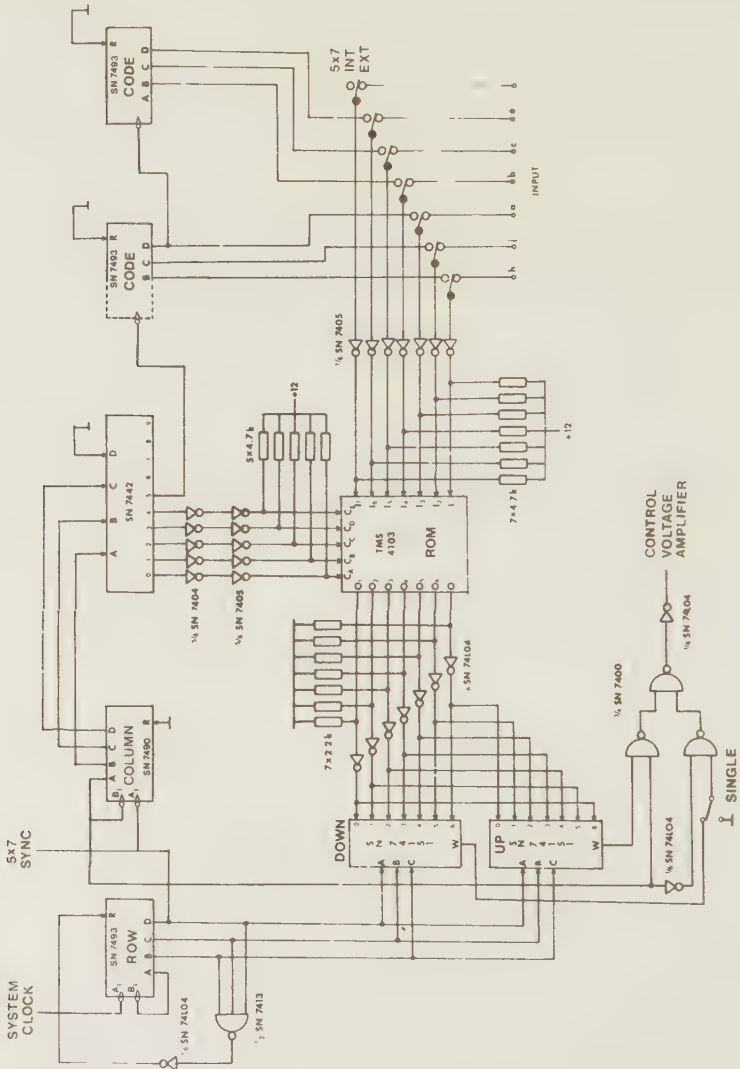


Figure 7.7. Circuit diagram of 5 x 7 matrix character generator.

In figure 7.7 the complete diagram of the 5 x 7 matrix character generator using a ROM (TMS4103) is shown. The system clock is first prescaled by two and thereafter connected to the B_i -input of the counter, consisting of a modulo seven counter. The output of the ROW counter controls the multiplexers UP and DOWN (SN 74151), one for the rising parts of the triangular wave starting to connect the bottom row of the matrix to the control voltage amplifier and another one for the falling parts of the wave starting at the top row and thereafter going through all the ROM outputs to the bottom one. In this way each matrix dot will be printed both during the rising and a falling part of the oscillation as shown in fig. 7.8. If the matrix dots are to be printed only during the rising parts of the triangular wave, the multiplexer DOWN used at the falling parts can be disconnected by means of a switch (SINGLE).



Figure 7.8. The use of both the rising and falling part for each matrix dot.

The output of the ROW counter changes the direction of the nozzle oscillation each time the ROM outputs are scanned either up or down, by means of the signal 5x7 SYNC connected to the nozzle oscillation control. The output of the ROW counter is also connected to the matrix COLUMN counter, the A output of which indicates the direction of the nozzle movement and is therefore used to select which of the multiplexer outputs shall be connected to the control voltage amplifier. The B, C and D outputs of the COLUMN counter, representing the column to be printed, are connected to the ROM

via a one-of-ten decoder (SN7442). Since the COLUMN counter is a modulo 8 counter and the matrix has 5 columns, 3 spacing columns will be inserted between the characters.

Output 5 of the decoder (SN7442) is used to increase the internal character CODE counter, thereby selecting the next character in the ROM to be printed, if the switch is in the "INT" position. Otherwise the output 5 of the decoder is used to fetch another character code from an external source.

7.5. A character generator with a matrix of variable size

In this character generator the information of the character matrix is stored in a recirculating shift register of 1024 bits. The number of matrix rows N_R can be selected between 1 and 99 by means of a thumb-wheel switch. Since the shift register has 1024 bits the maximum number of columns is $1024/N_R$.

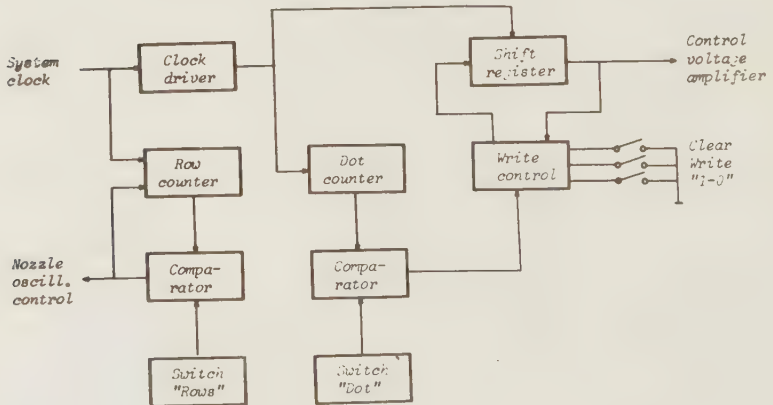


Figure 7.9. Block diagram of character generator using a matrix with variable size.

The system clock frequency is divided by N_R by means of a ROW counter, shown in the block diagram in fig. 7.9. When the counter reaches the number N_R set on the thumb-wheel switch "ROWS", the comparator will reset the counter. The comparator output is used to change the direction of the nozzle oscillation control.

A matrix dot counter is connected to the clock line of the shift register and identifies the position of the shift register. When the DOT counter reaches the number set on the thumb-wheel switch "DOT" the comparator will give a pulse the write control. At this pulse the write control inserts an "O" or "1" in the register if the switch "WRITE" is pressed. By means of the "CLEAR" switch the complete register can be set to either "O" or "1", depending on the setting of the switch "1-O". The information inserted in this way in the shift register will be recirculated simultaneously as it is connected to the control electrode to intensity modulate the ink trace on the paper.

The clock driver, shown in the complete circuit diagram in fig. 7.10 is necessary, since the shift register used (Intel 1402) requires a two phase non-overlapping clock. This is achieved by letting the system clock trigger a one-shot MC with a pulse length of 200 ns and by means of a J-K flip-flop connecting the short clock pulse from the one-shot to alternating the ϕ_1 and the ϕ_2 clock inputs of the shift register.

The ROW counter, consisting of two SN 7490, is connected together with the thumb-wheel switch "ROWS", to the comparator by six exclusive-or gates and an 8 input NAND-gate to gate the comparisons of the different bits together. The comparator output resets the counter and controls the nozzle oscillation by means of the nozzle oscillation control.

Since it is important to maintain a constant phase between the intensity modulation signal generated by the shift register and the mechanical oscillation of the nozzle which is governed by the ROW counter, it is necessary to assure that the mechanical oscillation is at its

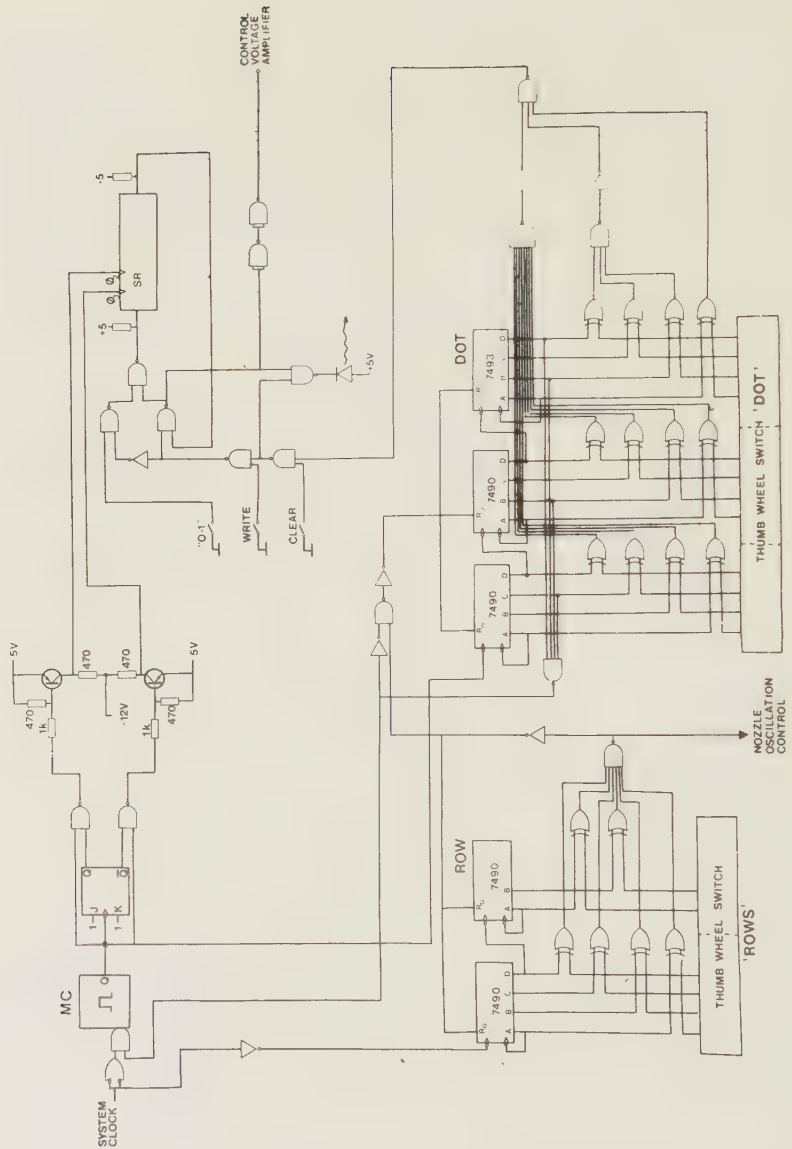


Figure 7.10. Circuit diagram of character generator with a matrix of variable size.

starting position when starting a new read out cycle from the shift register. This is obtained in the following way.

The clock input of the DOT counter is connected to the clockdriver before the generation of the two clock phases required for the shift register. When the counter reaches 1024, this position is decoded by a 4-input NAND-gate, which then stops the one-shot in the clockdriver. By this both the shift register and the DOT counter will be stopped, while the ROW counter continues. This is valid until the DOT counter is reset, which occurs when the DOT counter has reached 1024 and the ROW counter N_R . At the moment the DOT counter is reset to position zero and the shifting of the register starts again in phase with the nozzle oscillation, represented by the ROW counter.

The DOT counter position is compared with thumb-wheel switch "DOT", in the same way as the ROW counter. During the position "DOT" the comparator output will be low. If the switch "WRITE" is pressed the comparator output will disconnect the recirculating of the register at the "DOT" position chosen by the switch "DOT" and an "O" or "1" will be inserted at that position depending on the position of switch "O-1"

The entire register will be set to "O" or "1" if the switch "CLEAR" is set and the switch "WRITE" is pressed. The output of the register, connected to the control voltage amplifier, is gated with the comparator output to display the information in the position set on the thumb-wheel switch "DOT" by means of a light emitting diode. In this way it is easy to see if a "1" or "O" is present at the position "DOT".

7.6. Results

The 5×7 matrix generator has been used mainly to test different electrode systems, paper/nozzle distances, ink qualities etc. which will not be reported here. However, some of the results obtained with the character generator using a matrix with a variable size will be presented in this section. First, different methods to print information using 5×7 matrix characters will be discussed, whereafter some print samples of characters using larger matrices will be shown.

To get maximum print rate using 5×7 matrix characters and a triangular wave for the nozzle oscillation, the representation of the matrix dots as shown in fig. 7.11, seems to be suitable.



Figure 7.11. Representation of the matrix dots by the ink trace.

However the non-parallel ink traces will make the characters almost non-readable, as can be seen by the print sample in fig. 7.12.



Figure 7.12. 5×7 matrix characters, using the matrix dot representation shown in fig. 7.11.

By using only the rising part of the triangular wave for each of the matrix columns instead, the problem with the non-parallel ink traces can be avoided. In fig. 7.13 print samples using this matrix dot representation at different print rates are shown.

a)	150 ch/s	PRINT	PRINT	PRINT
b)	180 ch/s	PRINT	PRINT	PRINT
c)	240 ch/s	PRINT	PRINT	PRINT
d)	360 ch/s	PRINT	PRINT	PRINT
e)	450 ch/s	PRINT	PRINT	PRINT

Figure 7.13. Print samples of 5×7 matrix characters where each character column is printed during the rising part of the nozzle oscillation only.

The limited bandwidth of the Mingograph galvanometer will cause the nozzle oscillation to be more sinusoidal in spite of the fact that the current through the coil of the galvanometer is triangular. Consequently the deflection speed of the nozzle varies, because of which the height of the row in the middle of the matrix will be larger than that of the top and bottom rows of the matrix. This is especially obvious in the character "p" in the figure.

This error, due to the sinusoidal nozzle oscillation, can be compensated by varying the print time of a matrix element, depending on its position within the matrix. In fig. 7.14 the heights of the matrix rows, numbered with 1 from the bottom, are shown for some attempts to compensate the sinusoidal nozzle oscillation by using different numbers of clock periods for the matrix elements in different rows.

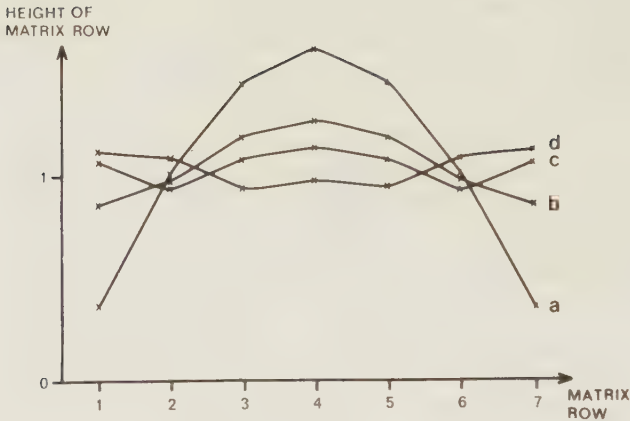


Figure 7.14. Compensation of varying nozzle deflection speed due to sinusoidal nozzle oscillation by means of different numbers of clock periods for the matrix elements.

Numbers of clock periods per matrix element in a column:

- a) 1, 1, 1, 1, 1, 1, 1
- b) 2, 1, 1, 1, 1, 1, 2
- c) 5, 2, 2, 2, 2, 2, 5
- d) 9, 4, 3, 3, 3, 3, 4, 9

As can be seen from the figure, the theoretical height of the top and bottom rows of the matrix will be less than a fourth of the middle one, if the same pulse length is used to print all matrix elements.

However, if the printing time for the elements of the top and bottom rows are twice as long as the print time of the other rows, the height of the top and bottom rows will be about 70% of the middle one. To decrease this undesired variation further, larger numbers of clock pulses for the print-time for each of the matrix elements have to be used. Due to the lower writing speed of the ink jet and by that the higher density (cf. chapter 4) at the top and

bottom rows of the character matrix, we had the subjective impression that the somewhat shorter print-time of these rows, when a compensation according to b in the figure was used, gave the best result. In fig. 7.15 print outs using this compensation of the sine wave shaped oscillation are shown for different print rates.

a)	150 ch/s	PRINT	PRINT	PRINT	PRINT
b)	180 ch/s	PRINT	PRINT	PRINT	PRINT
c)	240 ch/s	PRINT	PRINT	PRINT	PRINT
d)	360 ch/s	PRINT	PRINT	PRINT	PRINT

Figure 7.15. Print samples of 5×7 matrix characters where the limited bandwidth of oscillation of the jet nozzle is compensated according to fig. 7.14.b.

To increase the density of the printout, both a rising and a falling part of the nozzle oscillation can be used to represent a matrix column. A print sample using this representation of the matrix is shown in fig. 7.16.

PRINT	PRINT	PRINT	PRINT
-------	-------	-------	-------

Figure 7.16. Print sample of 5×7 matrix characters where each matrix column is represented by both a rising and a falling part of the nozzle oscillation. (Print rate 150 ch/s)

However, this method is more sensitive to phase changes between the nozzle oscillation and the intensity modulation signal. If a phase shift of about 8.5° occurs, some characters will be unrecognizable, as can be seen from fig. 7.17.

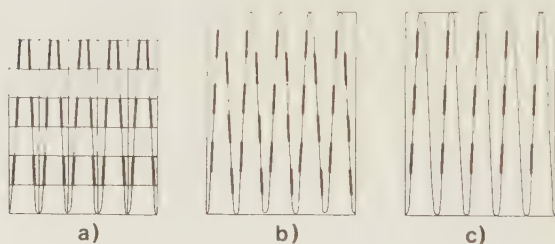


Figure 7.17. The influence of a phase shift of 8.5° on the appearance of the print out

- a) correct phase
- b) 8.5° phase shift
- c) 8.5° phase shift. Each column is represented by only a rising part of the nozzle oscillation.

If a Mingograph galvanometer is used as print head, no feedback of the exact position of the oscillating nozzle exists. Therefore the phase of the oscillation cannot be controlled. Consequently, the representation of a matrix column by both the rising and the falling part of the sine wave trace was not considered to be practical.

To retain the advantage of two ink traces for each column without having the drawback of phase-sensitivity, two rising parts of the nozzle oscillation can be used instead of only one to represent each matrix column. Print samples using this representation of the matrix together with the compensation of the sine-wave oscillation (cf. fig. 7.14.b) are shown in fig. 7.18.

a) 70 ch/s **PRINPRINPRINPRINPRINPRINPRIN**
b) 140 ch/s **FRINFRINFRINFRINFRINFRINFRINFR**

Figure 7.18. Print samples of 5 x 7 matrix characters, where each matrix column is represented by two rising parts of the nozzle oscillation and compensated for the sine-wave oscillation.

If extremely high print rates are not required, this representation of the character matrix seems to give the best character quality.

If characters of higher quality or more complex form are desired, the size of the matrix has to be increased. However, an increase of the number of columns will of course decrease the maximum print rate. As a reasonable compromise between print rate and quality a matrix size of 16 x 16 elements was chosen since this matrix size gives almost the maximum quality obtainable with the printing technology investigated here. A further increase of the matrix size did not result in any essential improvement of the quality due to the fact that the width of the ink trace on the paper, about $200\text{ }\mu\text{m}$, is already larger than the size of one matrix element ($160 \times 160\text{ }\mu\text{m}^2$).

In fig. 7.19, some characters of a Futura type font are shown. All

the characters are made up by a 16 x 16 matrix but with different thickness, which is apparent from the large characters.



Figure 7.19. Print samples of 16 x 16 matrix characters where each column is represented by a rising part of the nozzle oscillation. The samples have different fonts:

- a) Futura Light
- b) Futura Medium
- c) Futura Demibold
- d) Futura Bold

To represent the lower case characters *g*, *j*, *p*, *q*, either a matrix having more than 16 rows or a displacement of the whole matrix has to be used. The displacement of the whole matrix will be most economical both with respect to the size of the memory, storing the character matrices, and the writing speed of the jet. This displacement can be easily achieved by either adding a DC-current to the electric signal oscillating the nozzle or by making use of the second coils of the Mingograph galvanometer.

In fig. 7.20 both upper and lower case characters of the Futura Demibold font are shown. Since the memory size of the apparatus used is 1024 bits, only one character at a time can be printed. Because of this the figure is made up of many different samples.

Rag a gag

Rag a gag

Figure 7.20. Print samples of 16 x 16 matrix characters of a Futura Demibold type font.

To give an estimation of the possibilities of a 16 x 16 matrix, characters of a Roman font are shown in fig. 7.21. At a print rate of 25 characters/second the triangular shape of the driving signal to the galvanometer will be reproduced well enough to make a correction of the shape of the oscillation unnecessary. However, at higher print rates a correction has to be made.

Rag a gag

Rag a gag

ARM

ARM

Figure 7.21. Print sample of a 16 x 16 matrix characters of a Roman font.

To simplify the comparison of the different samples shown in fig. 7.13 - fig. 7.21 the values used in the different experiments are shown in fig. 7.22.

Figure	Print rate nozzle osc. freq. Paper speed Character density nozzle diameter Ink pressure Max writing speed of Matrix size Space columns Sine wave compensated Rising parts/column Falling parts/column												
	Ch/s	Hz	m/s	Ch/inch	um	kg/cm ²	m/s						
7.13 a	140	1000	0.31	12	20	50	9	5x7	2		1	0	
7.13 b	180	1250	0.38	12	20	50	11	5x7	2		1	0	
7.13 c	240	1670	0.50	12	20	50	15	5x7	2		1	0	
7.13 d	360	2500	0.58	15	20	50	25	5x7	2		1	0	
7.13 e	450	3100	0.82	14	20	50	21	5x7	2		1	0	
7.15 a	140	1000	0.30	12	20	50	9	5x7	2	x	1	0	
7.15 b	180	1250	0.45	10	20	50	10	5x7	2	x	1	0	
7.15 c	240	1670	0.54	11	20	50	13	5x7	2	x	1	0	
7.15 d	360	2500	0.66	14	20	50	19	5x7	2	x	1	0	
7.16	140	1000	0.32	11	20	50	8	5x7	2		1	1	
7.18 a	70	1000	0.20	9	20	50	8	5x7	2	x	2	0	
7.18 b	140	2000	0.37	10	20	50	18	5x7	2	x	2	0	
7.19	20	400			20	45		16x16			1	0	
7.20	20	400	0.04	12	20	45	3	16x16	4		1	0	
7.21	20	400	0.04	12	20	45	3	16x16	4		1	0	

Figure 7.22. The values of the different variables used in producing the samples in this chapter.

8. PRINTING OF MULTIPLE LINES OF CHARACTERS WITH ONE JET

8.1. Introduction

Different methods using the ink jet modulation principle, described by Hertz et al. (1967), can be used for printing characters on a paper moving with constant speed. For simplicity let us assume that the paper is moving in the direction of the text lines. To achieve highest possible printing rate, the number of nozzles shall be maximized. Thus, by using one nozzle to print each matrix row of characters on the lines (Erikson & Månsson 1975) a maximum printing speed, i.e. paper speed, of about 4 m/s can be reached.

However, the complexity of this system, involving n nozzles for each line of $m \times n$ matrix characters, is rather high. By using one oscillating nozzle for each text line instead, the number of nozzles could be decreased by a factor of n but the maximum printing speed will be decreased at the same time. Dependent on the limited writing speed of the ink jet and the fact that the present mechanical oscillators produce only sine wave shaped sweeps at these speeds, the printing speed will be reduced to a value of about $2.5/(m+2)$ m/s, if characters of acceptable quality and density are required.

It has been pointed out earlier (Sima 1966), that the ink jet galvanometers are able to generate a recording trace with an amplitude of about 40 mm on the paper, somewhat depending on the paper-nozzle distance. If one makes use of this capacity, several lines of characters can be printed simultaneously by one jet as shown in fig. 8.1. In this way the number of nozzles can be further reduced.

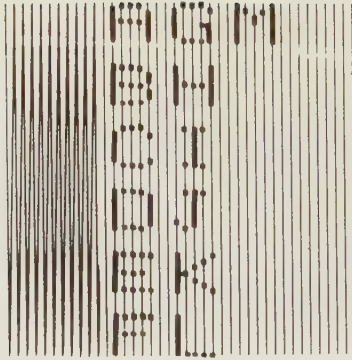


Figure 8.1. Multiple line printing.

Thus it is possible to print at least 9 lines, with a spacing of $1/6"$, with one nozzle. Since the oscillation frequency has to be reduced to ensure sufficient density and quality of the characters a sawtooth scan can be used in this case. This system configuration for multiple line printing is the simplest and cheapest but also the slowest one. In fig. 8.2. a comparison between the methods for a nine line system is made using the present technology.

Method	Number of nozzles	Practical print speed limit (m/s)	Estimated complexity of the electronics (Number of IC)
Fixed nozzle array	9xn	4	150
One oscill. nozzle/line	9	$\frac{2.5}{m+2}$	36
One oscill. nozzle	1	$\frac{0.3}{m+2}$	30

Figure 8.2. Comparison of different methods to print 9 lines of $m \times n$ matrix characters on a continuously moving paper.

In this section an apparatus will be described which uses the multiple line printing principle to print 6 lines of characters by means of one ink jet. It was constructed to be included as a print out facility in a research project at Lund University, Department of Clinical Physiology.

8.2. System configuration

At the Department of Clinical Physiology, University of Lund, a system has been developed (Jonsson 1974) which is used for recording, presentation and storage of electrocardiograms (ECG) by means of a minicomputer.

The hard-ware configuration is shown in fig. 8.3. The computer is a PDP-8/E (Digital Equipment) with 12 K 12-bit words. It has two disks with 1.6 M words each and a DEC-tape. The secretary's office has a video terminal (VT05). There are two ECG stations, one intended for exercise tests and one for ordinary ECGs. The latter is combined with the ECG cable system which connects the ECG laboratories and wards of the Lund University Hospital to the central ECG recording site.

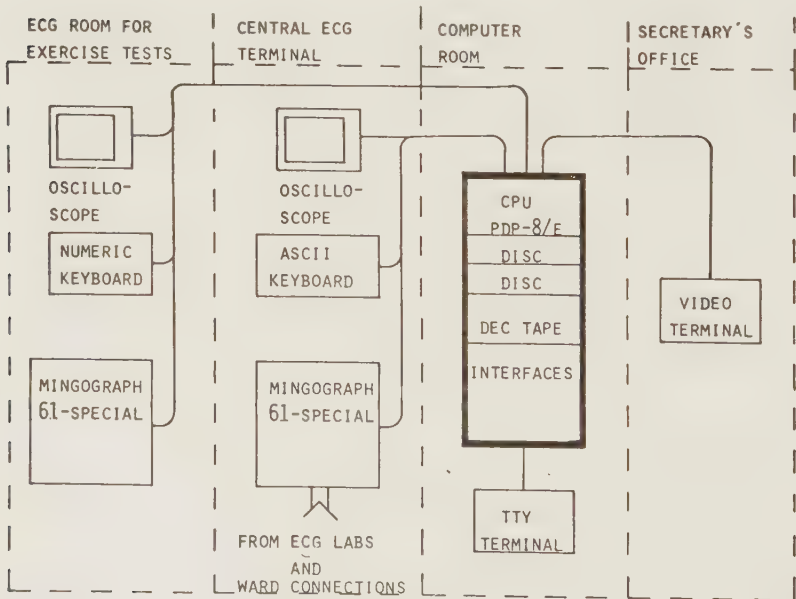


Figure 8.3. System configuration.

The Mingograph recorders have several special features, such as eight analogue channels which are connected to the computer input and 7 analogue channels from the computer output to the galvanometers. The Mingograph recorder allows direct analogue recording like any normal Mingograph recorder as well as the recording of computer signals which in magnitude are identical to the original analogue signals, e.g. ECG's. The computer controls stop and start, paper speed, recognition of a new sheet of paper and calibration. The galvanometer equipped with modulation electrodes for the printing of six lines of characters is also mounted inside the Mingograph recorder. This galvanometer requires a higher ink pressure than the galvanometers used for analogue recording, because of which it is fed from a separate ink pump.

A typical print out of this system is shown in fig. 8.4. The ECG recordings in the upper part of the print out are made by conventional analogue deflection of 7 ink jet galvanometers, while the six lines of characters in the lower part are printed by one intensity modulated ink jet galvanometer.

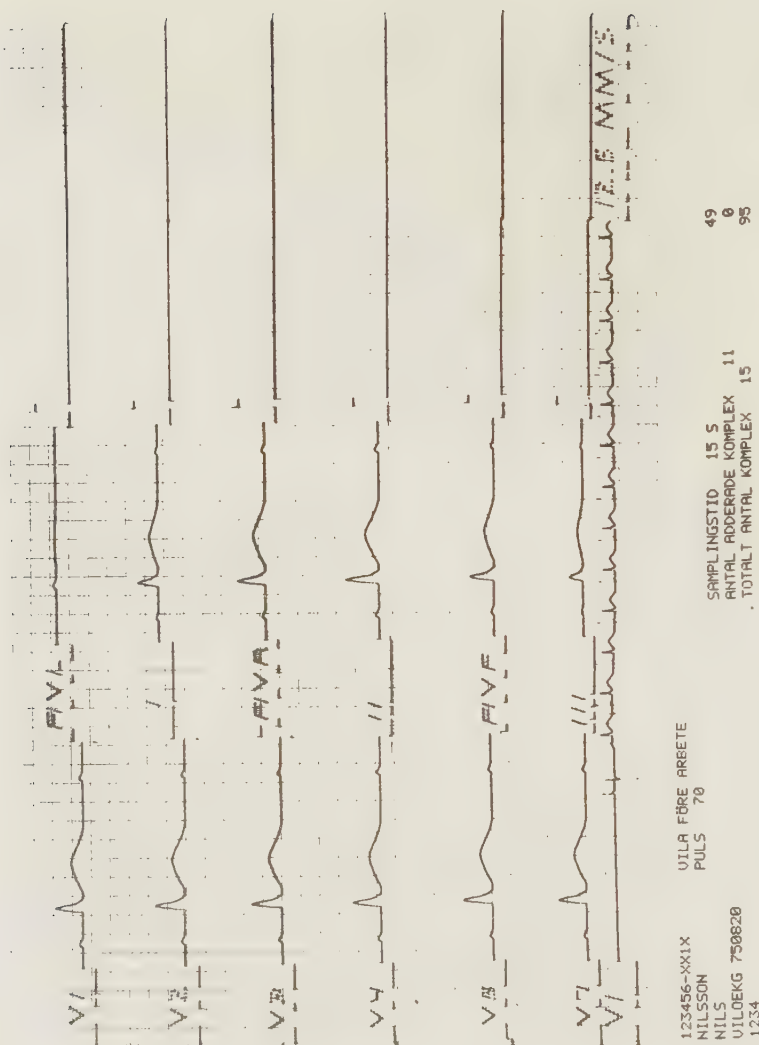


Figure 8.4. Typical print out of the ECG recording system.
(The large characters are printed according to another principle).

8.3. Principles of operation

Since the computer used has a word length of 12 bits, six bits ASCII code has been used for the information transmission to make possible a better packaging of the characters in the computer memory. A print out starts when the Control Flag CF from the computer interface, shown in fig. 8.5., goes high.

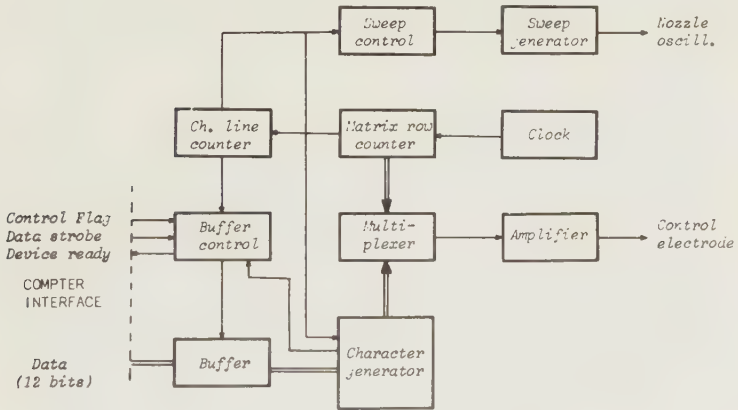


Figure 8.5. ... Block diagram of the electronics used for the multiple character scanning printer.

The buffer control has to respond to CF with requests for three data words, corresponding to six 6-bits coded characters, by means of the Device Ready Signal. At a Device Ready Signal the computer places a word on the outgoing data connections and a Data strobe. By means of the Data strobe the buffer control places the 12 bits information in the buffer as two 6-bits words. All this occurs while the nozzle makes an empty sweep.

When the nozzle has returned to its start position the print cycle begins by restarting the sweep. After a delay of 1 ms to stabilize the movement of the nozzle, position 0 in the buffer, corresponding to the uppermost character line (in the following called line 0) is connected to the character generator. The outputs of the character generator, column 1 of character line 0, are scanned by a multiplexer, which is controlled by the matrix row counter. In this way each dot of the first column will be connected to the control electrode for the intensity modulation of the ink jet. The duration of each dot is determined by the clock period. After spacing between the lines, the character counter is incremented. Thus the next character, corresponding to line 1, is connected to the character generator, the outputs of which will be scanned by the multiplexer etc.

When the first column of line 5 has been printed, the sweep control resets the sweep during 1 ms and after that restarts it again. Simultaneously a pulse at the column counter input of the character generator will increment the column counter in the character generator and thus connect column 2 to the outputs. One millisecond after the restart of the sweep the print out of column 2 of the six lines will start, just in the same manner as column 1. After the five first columns containing the 5×7 matrix character have been printed, two intermediate columns are inserted to generate a spacing between adjacent characters. During the last of these two columns, indicated by the counter output of the character generator, information for the next six characters is fetched from the computer by means of three Device Ready pulses. During the next five sweeps these characters will be printed. This will continue until the computer responds to the Device Ready pulse with a Control Flag (CF) signal. At the CF signal the printing will be stopped and all counters reset.

8.4. Electronic circuits

As the electronics are placed inside the computer no special line drivers or receivers have been used, as shown in fig. 8.6. At the start of the system, the Control Flag CF is low and thus the buffer address counter reset. When CF goes high, the one-shot will emit a Device Ready pulse, requesting data from the computer. The computer responds by placing new information on the data lines D0-D11 and a positive Data strobe pulse. This pulse will be connected to output SW0 of the buffer control since the counter is in position 0. At the positive flank of SW0 the information will be stored as one character in each of the first two 6-bits registers, SN74174, to the very left. At the end, i.e. the negative flank, of the Data strobe, the buffer address counter is incremented and the one-shot triggered. Thus new information will be requested from the computer. This time it will be stored in the next two 6-bits registers, since the counter is now in position 1. Also this time the one-shot will be triggered and request more information, which will be stored in the last two registers on the right.

Since SW3 is not connected to the one-shot no more data will be requested. During this time the nozzle has made an empty sweep, the last of the two spacing columns, which is indicated by the column output RDY of the character generator being high. When RDY goes low the counter will be reset and the triggering of the one-shot inhibited.

After the characters in the buffer and the first of the two space columns have been printed, RDY will be high again. This will indicate that the printing of the last space column is going on and that a new column of characters is required. The positive flank of RDY will trigger the one-shot, just as CF did the first time. Thus 6 new characters are fetched from the computer as before. This is repeated until the computer responds to a Device Ready pulse with a CF and by that inhibit new data requests.

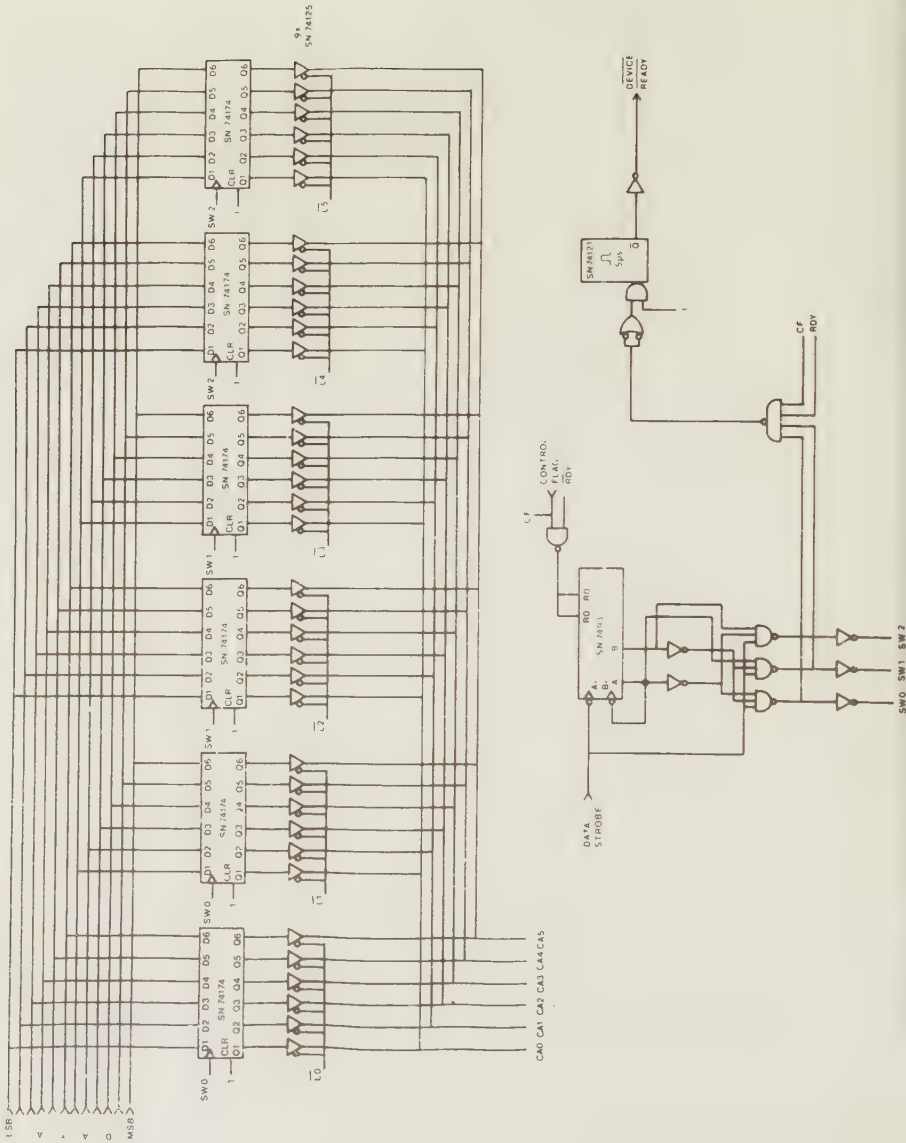


Figure 8.6. Circuit diagram of the Buffer and Buffer control.

Since the heart of the printer section of the electronics is the character generator MK 2302 P in fig. 8.7, this will now be examined more closely.

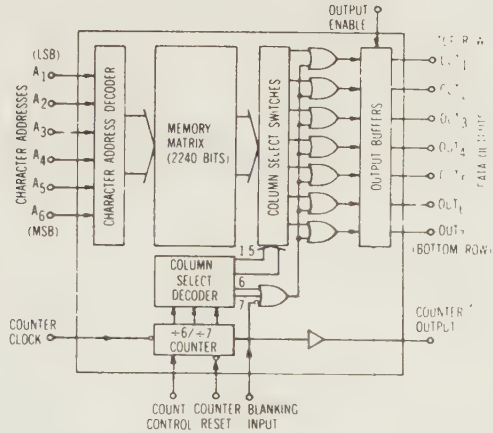


Figure 8.7. The character generator MK 2302 P.

Besides the normal ROM part, consisting of a memory matrix, its decoders, and an output buffer, a column counter is included in this character generator. Since the counter automatically inserts one or two spacing columns as shown in fig. 8.8, the matrix can be considered as a 7 x 6 or 7 x 7 matrix.

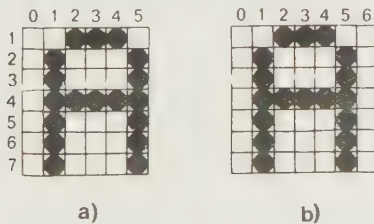


Figure 8.8. Intercharacter spacing.
a) one spacing column
b) two spacing columns

Either one or two space columns can be selected by the counter control. When the count reset input is low the column counter will be reset and thus the count output will be high, since it represents the column at the very left. Each time a negative flank occurs at the count clock input it will switch to the next column.

As long as CF is low almost everything in fig. 8.9. is stopped or reset. When the control flag CF goes high the sweep and the clock, consisting of a schmitttrigger gate in a feedback loop, starts. The clock increments the matrix row counter which scans the outputs of the character generator by means of the multiplexer SN74151. To prevent the counter from scanning the outputs again, when it reaches position 8, the D output is connected to the blanking input of the character generator. After insertion of a suitable number of spacing rows between character lines, the row counter resets itself simultaneously as it increments the character line counter SN7492. The one of ten decoder SN7442 of the line counter controls the information transmission between the buffer in fig. 8.6 and the character generator, by means of 36 three states buffers. When the sixth line has been scanned the one-shot to left will be triggered. The one-shot stops the clock and resets the sweep by discharging the capacitor during 1 ms, whereafter the second one-shot will be triggered. This one stops the clock, during the millisecond it takes to stabilize the movement of the restarted nozzle deflection. When the printing reaches the last of the spacing columns, equal to the first matrix column of the next columns of characters, the count output will become high and by that restart the fetching of new information from the computer.

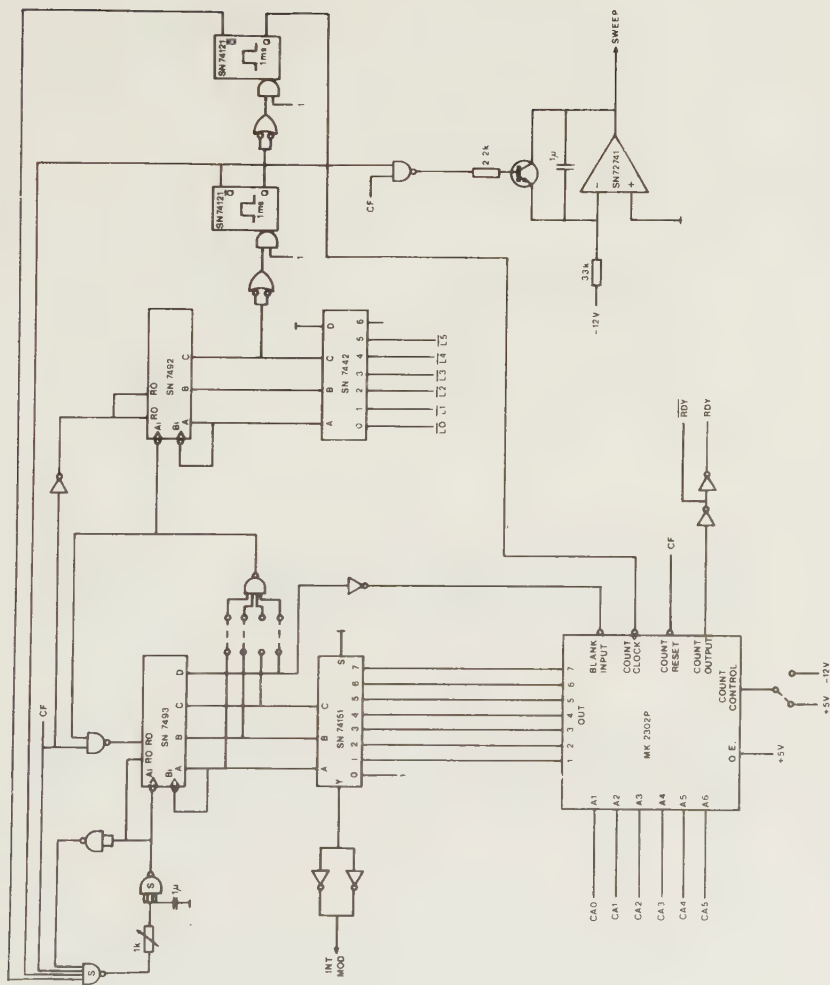


Figure 8.9. Circuit diagram of the character generator and its control circuits.

8.5. Results

In fig. 8.4, a reduced sample of the printout was shown, while in fig. 8.10 a part of a printout is shown in actual size. The paper speed was in both cases 25 mm/s to let the computer have time to compute all the information required for the printouts shown in fig. 8.4.

BBBBBBBBBBBBBB	LMNOPQRSTUVWXYZ
AAAAAAAAAAAAAA	ABCDEFGHIJKLM
DDDDDDDDDDDDDD	"#\$%&'()*+,-
CCCCCCCCCCCCCC	WXYZ[~]{} !"
FFFFFFFFFFFFFF	@9:;<=>?
EEEEEEEEEEEEEE	,./01234567
a)	b)

Figure 8.10. Part of a printout shown in normal scale. Paper speed 25 mm/s

a) diameter of nozzle 10 μ m

b) diameter of nozzle 20 μ m

If the paper speed is increased to 50 mm/s the writing speed of the ink jet can be calculated to be increased 2.3 times. Because of this the contrast of the characters is diminished which is demonstrated in fig. 8.11.

```

@BDEFHJLNPTBDEFHJLNPTUWZ~ " $%TDEFHJLNPTUWZ~ " $%
!"#$%&'()*+@BCDEFGHIJLMNOPQRS+@BCDEFGHIJLMNOPQRS
@BDEFHJLNPTBDEFHJLNPTUWZ~ " $%TDEFHJLNPTUWZ~ " $%
!"#$%&'()*+@BCDEFGHIJLMNOPQRS+@BCDEFGHIJLMNOPQRS
@BDEFHJLNPTBDEFHJLNPTUWZ~ " $%TDEFHJLNPTUWZ~ " $%
!"#$%&'()*+@BCDEFGHIJLMNOPQRS+@BCDEFGHIJLMNOPQRS

```

Figure 8.11. Part of a printout shown in normal scale.
 Paper speed 50 mm/s.
 (diameter of nozzle 10 μ m)

8.6. Extension of the system

The apparatus can easily be extended to print 10 lines of characters by adding the necessary buffer registers. In this case the decoder of the buffer address counter in fig. 8.6. has to be changed as shown in fig. 8.12.

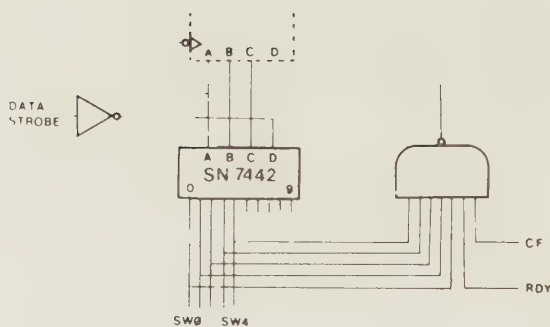


Figure 8.12. Change of the decoder of the buffer address to enable the printout of 10 lines of character.

Finally the character line counter in fig. 8.9 has to be replaced by SN7490 to allow the addressing of the extended buffer.

Of course it is possible to move the paper perpendicular to the text lines, instead, while using the same principle of printing. In this way a lineprinter can be built as sketched in fig. 8.13. The maximum print speed will probably be about 12 lines/s.

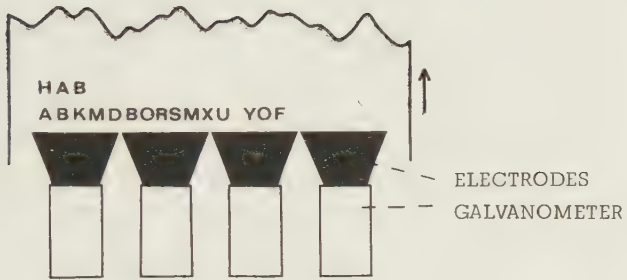


Figure 8.13. Proposal for a lineprinter capable of printing 80 ch/line at a speed of 12 lines/s.

9. INK JET TELETYPEWRITER FOR A COMPUTER TERMINAL

9.1. Introduction

For direct communication, between the operator and the computer terminal, typewriters and cathode ray tube displays with key boards are commonly used. While the CRT display offers the advantage of high speed and noiseless operation, hard copies cannot easily be obtained from these devices without extra cost. Because of this, mechanical teleprinters are still frequently in use as computer terminals in spite of their obvious disadvantages, i.e. low speed and high noise level.

Since a hard copy of the computer output is frequently very desirable it would be advantageous to improve the mechanical teletype by a printing system having higher speed and lower noise level. As a consequence some new mechanical printing systems have been introduced on the market during recent years, e.g. needle printers and daisy wheel printers. However, because of the limitations of these systems, certain non-impact systems are presently being developed for terminal typewriters. Many of these developments use different types of electrically controlled ink jets because of their speed and noiseless operation as well as their ability to print on plain paper (Kamphoefner 1972).

Besides other deficiencies, most of these ink jet printers are unable to print characters in an asynchronous mode, which is the normal mode of operation of a typewriter. Instead, most of them print an entire line at a time moving across the paper at constant speed. For this reason these devices are mostly used in connection with a CRT display where they can generate a plain paper copy of the information shown on the CRT. However, they do not have the ability to plot x-y-diagrams which often are also displayed on the CRT-screen.

Therefore, we decided to study the use of an oscillating ink jet nozzle as a printing element in a typewriter, which can be used as a computer terminal. This study resulted in the construction of an ink jet typewriter which has exactly the same properties as a conventional computer terminal typewriter except for speed and noise. Further, it is able to plot x-y-diagrams in the same way as is conventionally done by an x-y-plotter. Therefore, it should be an interesting hard copy alternative to the conventional CRT display as a computer terminal.

9.2. Principle of the ink jet typewriter

The method of character generation described in chapter 1.2. has been used in a printing head for a typewriter which is shown schematically in fig. 9.1. In this device a carriage C is moved step-

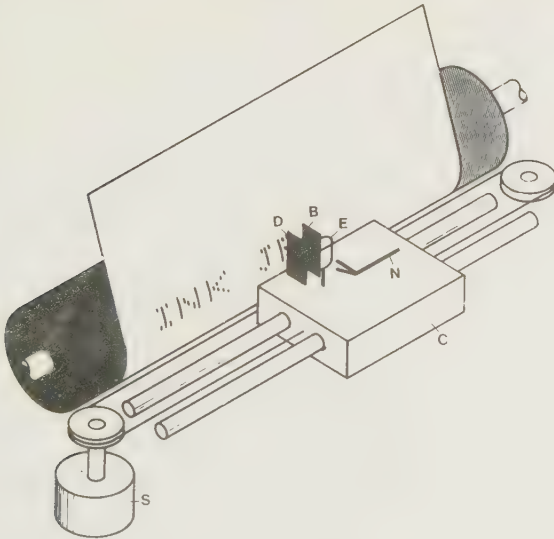


Figure 9.1. Principle of the typewriter. A step motor S drives the carriage C along the platen. On the carriage C an ink jet system consisting of nozzle N, control electrode E and deflection electrodes B and D is mounted.

wise by a step motor S along the paper on the platen. On the carriage C a nozzle N, oscillating in a vertical plane, is mounted. As in the case of the multiple line printer (cf. chapter 8), the nozzle oscillation used here has a sawtooth shape. Thus the ink jet from this nozzle will generate a sawtooth trace on the paper during movement of the carriage.

As described above, alphanumeric characters can be generated by the intensity modulation of the ink jet. This is accomplished by an electrode arrangement between the nozzle and the paper, as indicated in the figure, to which a suitable electrical signal is supplied.

Due to the vertical mounting of the electrodes, a special electrode system, already shown in fig. 2.6, was developed. Since the drying time of the printout on the paper is strongly dependent on the amount of ink deposited per unit area, a nozzle diameter of $15\text{ }\mu\text{m}$ is used since this jet diameter was found to make the best compromise between the density and the drying time of the printout.

The prototype of the ink jet typewriter was built on an IBM Selectric chassis, where all parts except the carriage for the printing head, the platen carrying the paper and the case were removed. However, this was later found not to be a good solution due to the large inertia of the carriage as well as the platen. Both of them have a rugged design to withstand the mechanical forces of an impact printer.

As can be seen from the block diagram in fig. 9.2 the typewriter can work either in local or remote mode. In the local mode it can be operated like an ordinary typewriter from the key board while in the remote mode it is controlled by a mini-computer or similar device. The selection between the modes is made by the input/output unit (cf. fig. 9.2) which accepts the ASCII code produced by the key board or mini-computer. Further, this unit contains a buffer memory for the ASCII code characters and the necessary

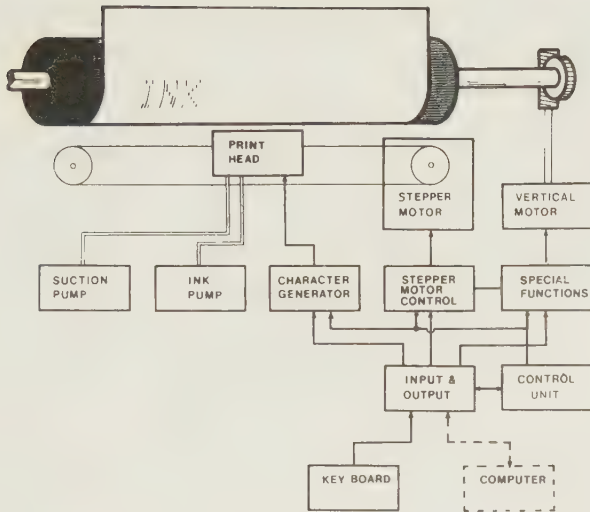


Figure 9.2. Block diagram of the ink jet typewriter.

circuits for the information transmission between the computer and the typewriter.

When a character is available from the input/output unit, the control unit initiates the step motor through the step motor control and, after a delay, also the character generator. As soon as a character is printed on the paper, the character generator sends a DONE signal to the control unit which will relay this signal to the computer if the typewriter is working the remote mode.

At present charter matrix sizes of 5 x 7 and 7 x 9 have been employed but matrices as large as 16 x 16 can be used, when integrated ROMs of this size become available at a reasonable price. This will increase the character quality appreciably. Since the

step motor makes 4 or 5 steps for each character, the frequency of the nozzle oscillating or the stepping of the motor has to be changed when the matrix size is altered to ensure constant width of the characters.

The ASCII codes for some control functions are recognized by a special functions unit, which in turn initiates the line feed and the stepper motor. The line feed is effected by a small DC motor (cf. fig. 9.2) equipped with an optical transducer to measure its rotation while the carriage return is brought about by reversing the step motor. Further, a special function is included which allows the increase of character width by making more than the normal 4 or 5 steps with the step motor per character and printing each matrix column of a character twice.

It was mentioned earlier that the present typewriter is also able to plot x-y diagrams in the same way as a CRT data display or a conventional x-y plotter. In this so-called plotting mode the oscillations of the ink jet nozzle are stopped and the control signals governing the plotting are decoded in the special functions unit. The line feed motor and the step motor, as well as the intensity modulation electrode, are then controlled by signals from the special functions unit. By moving the paper feed drum and the carriage C in a suitable way, the stationary ink jet can trace the diagram on the paper. In this plotting mode the resolution in both x and y direction is 0.5 mm.

9.3. Motion of the print head

As already shown in fig. 9.1 the carriage on which the print head is mounted is moved by a step motor. The perhaps most natural number of motor steps per character is equal to the number of columns of the character matrices. However, at the step rates used, the discrete steps of the motor rotation will be smoothed out by the inertia of the system. Therefore, no correlation between the

number of steps and the number of matrix columns is required.

Because of this a fixed number of steps is used, in the present typewriter, which is independent of the size of the character matrix. To obtain a character density of either 10 or 12 characters/inch without mechanical changes, 5 respectively 4 motor steps were used to print one character. This is accomplished by a step motor Philips PD20 together with a wheel of suitable size driving the carriage via a cord. As pointed out above, the typewriter can be operated in either a continuous mode from a computer or a discontinuous mode, where the print head actually stops between each character. In the first case the characters are printed "on the fly", i.e. while the carriage is in continuous motion with a constant speed v_c . On the other hand, the discontinuous operation requires an acceleration of the carriage to the predetermined carriage speed v_c before the printing can be started to avoid distortion of the characters.

Fig. 9.3 shows the theoretical (curve a) and actual (curve b and c) movement of the carriage when printing a single character (curve c) or two characters immediately following each other (curve b) as a function of time. The curves b and c are measured experimentally, while curve a is constructed from the positions of the electrical pulses driving the step motor and represents the electrical angle of the motor. The print method used here requires that the print head moves with constant speed when printing a character. Therefore, if the print head starts from rest, the print out can be started only after a time delay τ_1 which of course is the same for the single character (curve c) and double character (curve b) print out cycle. This time delay should be chosen in such a way, that a suitable spacing between the character is obtained.

If only one character is to be printed, the print head will be stopped immediately after the print out (curve c). However, in the case where a second character is to be printed immediately follow-

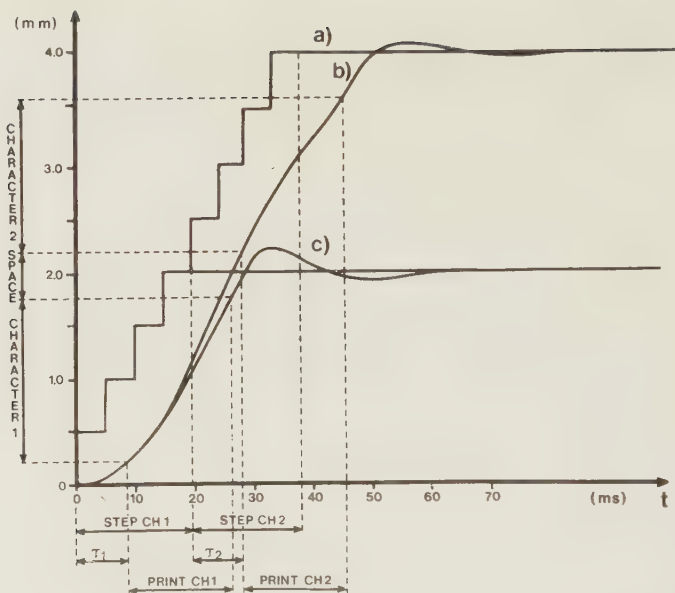


Figure 9.3. Motion of the print head
 a) electrical signal
 b) motion caused by 8 steps of the step motor
 c) motion caused by 4 steps of the step motor

ing the first, it is more advantageous not to decelerate the print head between the characters but to keep it in continuous motion as shown in fig. 9.3 curve b. To ensure a correct character spacing, a different delay time τ_2 has to be used in this case before starting the printout cycle of the second character, the length of which depends on the speed of the print head motion v_p . As can be seen from fig. 9.3 this actually requires that the actuation of the step motor for character 2 is started already during the printout cycle of character 1. This time delay τ_2 is used also if more than two characters are to be printed out at maximum speed.

Since the time delays τ depend on the speed of the print head immediately before the step motor is started, the step motor is allowed to start either from rest or continue at normal stepping speed only. In this way only two time delays τ_1 and τ_2 are required, which are supplied by the monostable multivibrators PRINT DELAY I and II and fig. 9.8.

As can be seen from fig. 9.3 the speed of the print head during the print out cycle is not quite constant due to a small resonance of the mechanical system at a frequency of about 25 Hz. This has a slight influence on the width of the characters which, however, is barely noticeable in the present application and therefore disregarded.

The selected step motor worked adequately up to step rates of about 240 steps/s. This speed is equal to a print rate of 50 characters/s, is a character density of 10 characters/inch is used.

Since the print rate is limited by the step motor in the present typewriter, sawtooth shaped oscillations of the ink jet nozzle could be used in this case, which simplified the design of the control electronics.

9.4. Input and output unit

By means of the input/output unit, the typewriter can be operated either in local or remote mode. The selection between these two possibilities is made by means of the mode switch. In local mode the characters are fetched from the keyboard and the ASCII codes are stored in an 8 bit code buffer in fig. 9.4.

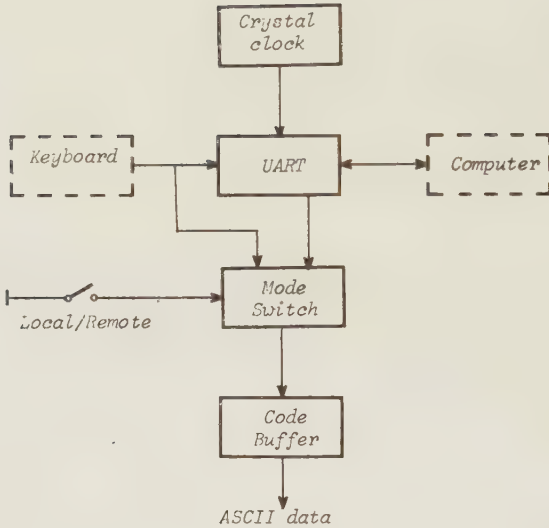


Figure 9.4. Block diagram of the input/output unit.

The data transmission from the keyboard is in parallel form, but in remote mode the transmission is made in a standard serial Teletype format, shown in fig. 9.5.



Figure 9.5. Data transmission format in remote mode.

To make the serial/parallel conversion and the insertion of start and stop bits during transmitting of data to a remote device, and the reverse at receiving, a Universal Asynchronous Receiver Transmitter (UART) is used. This unit contains all the necessary logic to control the transmission by means of two wires: one for receiving and one for transmitting. To be able to distinguish between two consecutive "1" or "0", the received signal has to be synchronized with a clock. Since the difference between the clock frequencies of the receiving and transmitting unit must be less than 4.5 % to maintain synchronization during the transmission of a character, a crystal controlled oscillator is used as a clock. The clock frequency connected to the UART is internally divided by 16 to reset, by means of the start bit, the phase difference between the clock and the received signal.

In the circuit diagram of the input/output unit, fig. 9.6, the crystal clock can be studied in more detail. The crystal frequency of 9.625 MHz can be scaled down to two presettable values by means of four counter sections. When the counter overflows, equal to the fall of the D-output of the last counter section, the last two sections will be loaded by one of two preset values, via the Ap-Dp inputs. Thus, if the value, preset by means of the jumpers, is N, the clock frequency f_c will be

$$f_c = \frac{9.625 \cdot 10^6}{8 \cdot 10 \cdot (256-N)} = \frac{120.3}{256-N} \text{ kHz} \quad (9.1)$$

and the Baud transmission rate T_B because of frequency division inside the UART

$$T_B = \frac{f_c}{16} = \frac{7520}{256-N} \text{ Bauds} \quad (9.2)$$

Since each character consists of one start bit, 8 data bits and 2 stop bits, the character transmission rate T_c will be 11 times lower:

$$T_c = \frac{T_B}{11} = \frac{684}{256-N} \text{ ch/s} \quad (9.3)$$

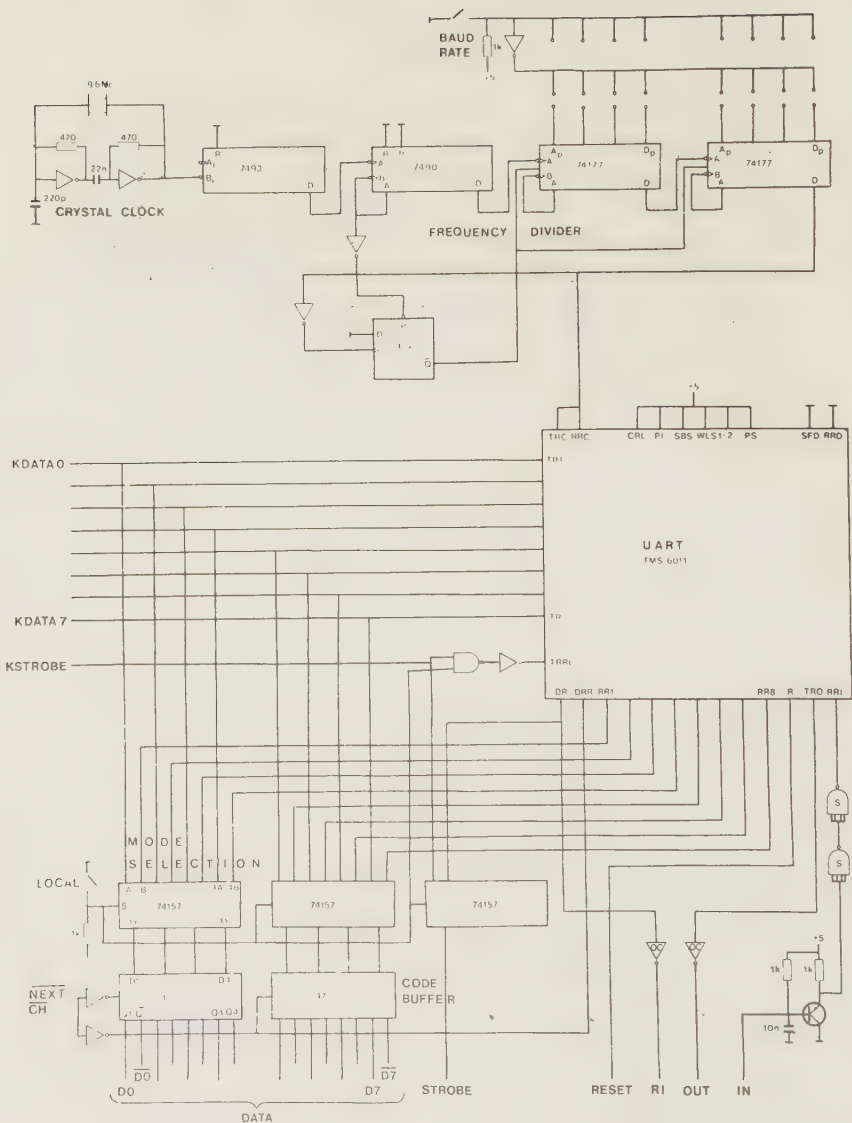


Figure 9.6. Circuit diagram of the input/output unit.

The transmission rates have been chosen as 110 Bauds, the standard teletype rate and 1200 Bauds. The later rate will make use of the maximum print rate of the typewriter.

Since the typewriter is not capable of printing 1200/11 characters continuously, the transmission has to be stopped occasionally. This is achieved in the following way. When a complete character has been received by the UART, it will automatically be transferred to an internal buffer and the Data Ready (DR) output goes high. The Remote Inhibit, equal to DR, will stop the transmitting of the remote device by gating the clock pulses to the Transmitter Register Clock (TRC) input of its similar UART.

When the typewriter has completed the printing of the previous character, it will transfer the character in the UART buffer through the mode switch to the code buffer and thereafter reset the DR signal, thus restarting the transmitting of the remote device.

9.5. Control unit

The control unit, the block diagram of which is shown in fig. 9.7, supervises and synchronizes the other units.

When the strobe signal from the input/output unit rises, indicating that a character is available at the inputs of the code buffer, a flip-flop, NEW-CHaracter, will be set. If the printing of the previous character is READY, then the next character is stored in the code buffer and the step motor is started by means of the STEP flip-flop. When the step motor has made the correct number of steps, it will be stopped since the STEP flip-flop is reset by the Motors Ready signal MR.

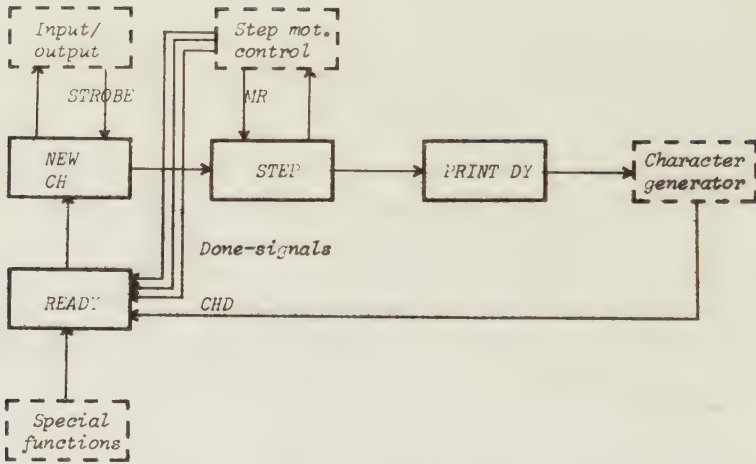


Figure 9.7. Block diagram of the control unit.

To allow the step motor to accelerate before the start of printing, a suitable delay, PRINT Delay, is inserted between the STEP flip-flop and the character generator.

As soon as the entire character is printed, the READY flip-flop will be set by means of the CHaracter Done (CHD) signal. If a new character has arrived at the inputs of the code buffer during printing, it will now be stored in the buffer and the step motor started as before. If operations corresponding to codes other than normal characters are to be executed, e.g. a plot instruction, Line Feed Carriage Return or a Control Code (CC), almost the same sequence will occur.

Since the above explanation of the function of the control unit is somewhat simplified, a more detailed presentation, using the circuit diagram in fig. 9.8, will follow. The NEW CHaracter flip-flop indicates that a new character, waiting to be printed, is present at the inputs of the code buffer. The start of the step motor can occur in three different ways, depending on the present state of the printing.

- a/ If no character has been printed for some time, NEW CH will set the STEP flip-flop and thereby start the step motor.
- b/ When the character arrives before the previous character has been printed completely, the STEP flip-flop will be locked in the "set" state and thus prevented from being reset by MR. In this way the motor will work with a constant stepping rate which avoids acceleration of the print head as long as new characters are available at a sufficiently high rate.
- c/ To circumvent oscillations of the step motor, which occur when it is stopped, a one-shot STEP Delay prevents it from being restarted during a time long enough to let the oscillations die out. If this precaution is not taken, the acceleration of the print head will not always be the same, which would result in unequally spaced matrix columns. This will not decrease the print rate, but introduce a time delay between the hitting of a key and the start of the actual print out equal to STEP Delay, at maximum.

Depending on whether or not the step motor has to be accelerated, the STEP flip-flop will or will not make a 0-1 transition. This in turn selects one of the two different print delays PRINT DY I or PRINT DY II, which are used to delay the print out until the step motor has accelerated to normal speed.

The character to be printed will be stored in the code buffer, by means of the one-shot NEXT CHaracter, which is triggered when NEW CH · STEP DY · READY is true. This signal NEXT CH will also reset the READY and NEW CH flip-flops. Depending on the type of the last character code, the done signal to the READY flip-flop will arrive from different locations. If for instance it was a normal character the character generator will send a CHaracter Done signal. The done signal, after instructions causing movements of the heavy platen, e.g. LFD, will be delayed (READY Delay) somewhat, to let the platen stop first. If for instance two conse-

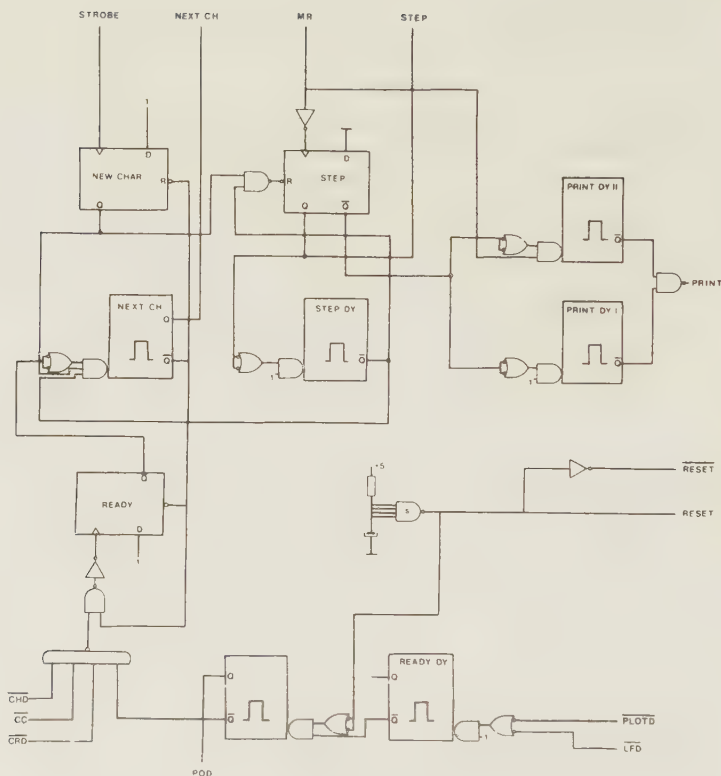


Figure 9.8. Circuit diagram of the control unit.

cutive Control Codes arrive another problem will arise. Since a Control Code is executed immediately, the signal itself, CC, is used as done signal. However, to distinguish between two consecutive Control Codes, the edge triggered set signal to the READY flip-flop has to be strobed by NEXT CH.

9.6. Special functions

The data received from the keyboard or a computer consists of a 7-bit code and a parity bit. The codes 040_8 - 137_8 are used for printable characters, i.e. the 26 capital letters, the 10 numerals and 28 special characters as \$, ?/+ etc. Since the small letters are not used in this typewriter, the codes reserved for these, 141_8 - 172_8 , are not used. Of the codes 000_8 - 037_8 , reserved for control purposes, 12 are used, namely Line Feed 012_8 , Carriage Return 015_8 , control N and control 0 016_8 - 017_8 and controls P-W 020_8 - 027_8 . The codes 016_8 and 017_8 , also named Shift In and Shift Out, are normally used to change the color of the print out but are here used to change the size of the characters.

To control the plotting of x-y diagrams codes 020_8 - 027_8 are used in the following way. The four most significant bits of the code are used to identify the plot instructions. The least significant bit is used to determine if the plotted line shall be horizontal or vertical. The other two bits are used to control the plotting direction and the intensity (on or off) of the line respectively as shown in fig. 9.9.

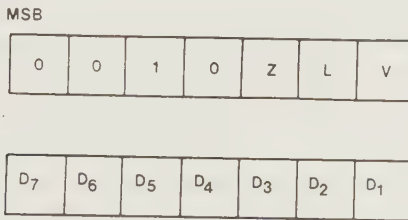


Figure 9.9. Format of a plot instruction

Z Intensity of the line (line/no line)
 LV Direction of plotting
 00 Right
 01 Down
 10 Left
 11 Up

D₇-D₁ Length of the plotted line

Normally, an incremental plotter will make only one step in each direction for each plot command. If the same technique were to be used here, and the transmissions rate between the computer and the typewriter is 110 Bauds, plotting of a line of 100 mm, corresponding to 200 steps of 0.5 mm, would take 20 seconds. This plotting speed is too low for practical purposes, therefore the next code received is used to determine the length of the line to be plotted, i.e. the number of steps of the motor. In this way a line of a maximum length of $2^8 \times 0.5 \text{ mm} = 128 \text{ mm}$ can be generated by a single plot instruction, consisting of two words. Now the plotting speed will not be limited to the transmission rate between the computer and the typewriter, but by the speed of the motors. In the horizontal direction the speed is 250 steps/s and a line 100 mm is plotted in 0.8 seconds instead.

If the first code of a print instruction is present in the buffer, its four most significant bits will be decoded by a Nandgate, PLOT DECODEr in fig. 9.10, which stores the Z, L and V values in flip-flops and sets the flip-flop PL. Since the PLOT flip-flop is still in its zero state and $\overline{\text{CR}} \cdot \overline{\text{LF}} \cdot \overline{\text{CH}}$ is true the output of the Control Code DECODEr will go low and demand that the next code be transferred to the buffer by means of the control unit. The next code is the second code of the plot instruction, which can have all values and therefore has to be prevented from being decoded as, for example, a numeral. Because of this all the decoders are disconnected by the flip-flop PL, which sets the two most significant bits to one at the inputs to the decoders. At the arrival of the second code of the plot instruction to the buffer, the signal NEXT CHAracter, generated in the control unit, sets the PLOT flip-flop, which starts the execution of the plot instruction. During plotting the ink jet nozzle will not oscillate but be directed straight ahead all the time, because of which the writing speed of the jet will be decreased by a factor of 10 or more. To compensate for this low writing speed, some of the ink is pulsed away by the one-shot ZPL, which is connected to the input of the intensity control amplifier. In this way deposition of too much ink on the paper and the conse-

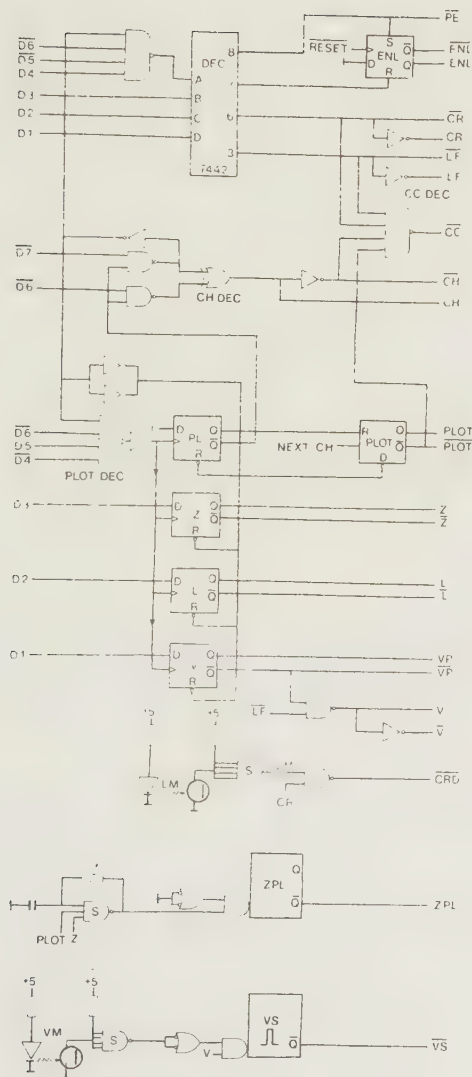


Figure 9.10. Circuit diagram of the special function unit.

quent run out around the plotted line is avoided.

To recognize the Carriage Return, Line Feed, Shift In and Shift Out Instructions, a one-of-ten decoder, DEC, is used. Its outputs corresponds to the codes 010_8 - 017_8 , including the instructions mentioned above. If the Shift Out key (control N) is depressed the ENLarged character flip-flop is set. The typewriter will, after this, print enlarged characters until the Shift In key (control 0) is hit.

To shut off the character generator when the code is not in the interval 040_8 - 137_8 a CHaracter DECoder, consisting of an exclusive-or gate, is used. If the code is not recognized as a Carriage Return, Line Feed, CHaracter or the second code of a plot instruction, i.e. $\overline{CR} \cdot \overline{LF} \cdot \overline{CH} \cdot \overline{PLOT}$ is true, the Control Code DECoder will classify it as a control code. Such control codes can mean the first plot instruction, character size instructions and other codes not used in the present typewriter.

Also included in this unit are the interfaces of two optical transducers: Left Margin and Vertical Motor. The Left Margin transducer (LM) is used to detect when a Carriage Return is completed and the Vertical Motor transducer (VM) to indicate the motion of the platen, by means of a disc with four slits mounted on the axis of the vertical motor.

9.7. Motor control

When the STEP flip-flop in the control unit rises to a "1", the step motor or the line feed motor will make a certain number of steps, depending on the type of code present in the buffer, e.g. plot instruction, normal character, or carriage return. To control the rate of the step motor a STEP CLOCK, shown in the upper left corner of fig. 9.11, is used. If $\overline{V} \cdot \overline{VS} \cdot \text{STEP} \cdot \overline{CR}$ is assumed to be true the clock will oscillate with a frequency determined by the

time constant R_1C_1 . The number of clock pulses, equal to the number of steps of the step-motor is counted by means of a STEP counter (2 x SN7493). The value of this counter is compared with a present value of one of four comparators, i.e. Line Feed COMPArator, CHAracter COMPArator, ENLarged character COMPArator and PLOT COMPArator, depending on the kind of code in the buffer.

If a normal character is to be printed, the comparison will occur in the CHAracter COMPArator since only this comparator is enabled by CH and $\overline{\text{ENL}}$. Depending on the wiring of the jumpers at its inputs, it will give out a signal after 1 to 16 steps. Since each step is equal to a horizontal displacement of the print head of 0.5 mm, a wiring of the jumpers corresponding to four steps will give rise to a character density of 12 characters/inch and a wiring corresponding to five steps 10 characters/inch. The output of the CHAracter COMPArator gated together with the outputs of the other comparators in an OR-function makes up the Motors Ready signal, which resets the STEP counter and the STEP flip-flop in the control unit.

If instead an enlarged character is to be printed, the displacement of the print head is determined by the ENLarged character COMPArator and the jumpers at its inputs.

A Carriage Return code in the buffer, detected by the special functions unit will change the direction of the step motor by means of the NAND-gate in the upper right corner of the diagram. Further, the STEP clock, the time constant of which will be changed to R_2C_2 to decrease the return time of the carriage will oscillate until the print head reaches the left margin, detected by a transducer (cf. 8.6) where the step motor will be stopped by the Carriage Return Done signal from the special functions unit, by setting the Motors Ready signal.

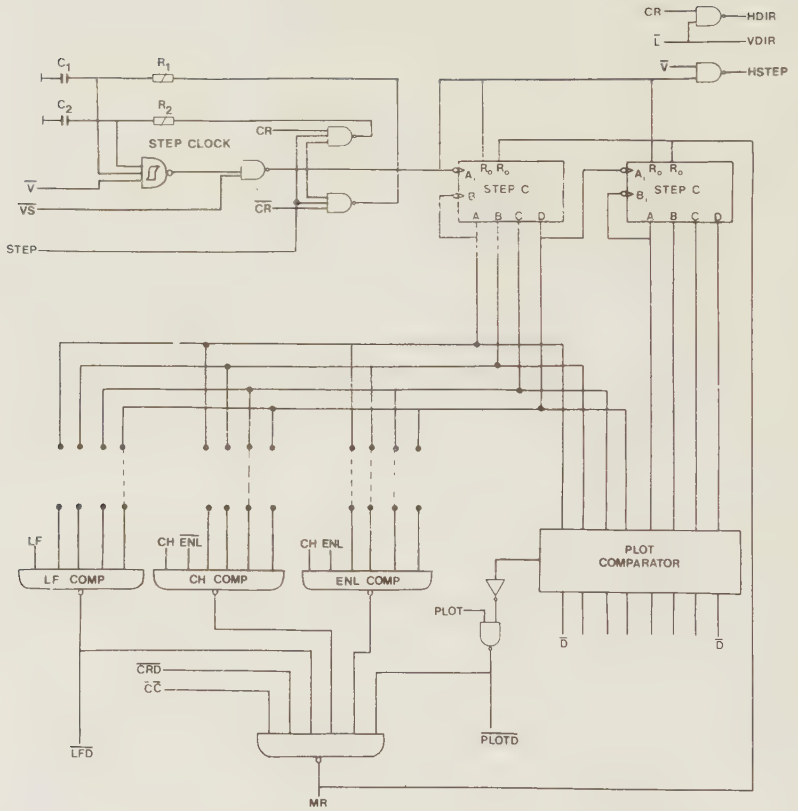


Figure 9.11. Circuit diagram of motor control.

Because of its size, a step motor could not be used for the rotation of the platen in the present typewriter and, therefore, a small DC-motor has been used instead. To control its movement, a disc with four slits was mounted on its axis, which cuts out the light beam of an optical transducer four times for each revolution of the DC-motor.

If the paper is to be moved vertically, the STEP CLOCK is stopped by means of the inverted value of the signal Vertical, which also starts the DC-motor and the pulses from the transducer, Vertical Steps VS corresponding to a displacement of the paper of 0.5 mm, are applied to the STEP COUNTER input instead of the STEP CLOCK pulses. If the code in the buffer corresponds to a line feed, the pulses from the transducer, Vertical Steps, will be counted by the STEP COUNTER in the same manner as for a horizontal displacement of the print head and thereafter compared with a preset value in the Line Feed COMParator.

At the arrival of the second code of a plot instruction to the buffer, either the motor moving the platen or the print head will start in the correct direction and the displacement is measured by the STEP COUNTER. When the counter reaches the value determined by the second code of the plot instruction, stored in the buffer, the PLOT COMParator will stop the motor used, by means of the signal Motors Ready. A detailed circuit diagram of the PLOT COMParator, using exclusive-or gates, is shown in fig. 9.12.

The direction of the motors, during plotting is controlled by the signal Left, generated in the special functions unit, in the upper right corner of fig. 9.11. When $L = 1$ the print head will move to the left and the paper downwards.

The last alternative of code types, Control Codes, will stop the motors immediately since it is directly connected to the Motors Ready signal, equivalent to a comparison of the STEP COUNTER with zero.

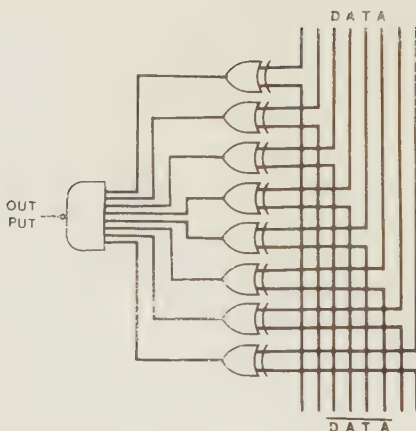


Figure 9.12. The plot comparator.

9.8. Character generator

The principle of the character generator is almost the same as that in the 5 x 7 matrix character generator of the experimental test apparatus described in chapter 7.4, but will nevertheless shortly be discussed here. In chapter 9.5 it was mentioned that a signal PRINT is generated in the control unit with a suitable time delay after the start of the step motor. This signal is connected to the clock input of the PRINT flip-flop in fig. 9.13, which thus will be set if the code in the buffer corresponds to a CHARACTER. At the setting of the PRINT flip-flop, the sawtooth shaped oscillation of the nozzle will be started by resetting the NOZZLE RETURNING signal. After a time delay determined by the one-shot START DELAY, to let the relaxation oscillations of the nozzle die out, the matrix DOT CLOCK and thereby the print out of the first column of the

character will be started. The six least significant bits of the code buffer in the input/output unit are connected to the character inputs of the ROM. Since the character generator only will be started if $CH=1$, i.e. the code is in the interval 040_8-137_8 , the addresses of the ROM code inputs 040_8-077_8 will represent the same codes but the codes 100_8-137_8 will be represented by 000_8-077_8 at the code inputs of the ROM. The outputs of the ROM (0_1-0_7) represent one of the 9 matrix rows, because of which the ROW COUNTER is connected to the four row inputs, A_6-A_9 of the ROM, thereby determining which row shall be connected to the outputs.

When the ROW COUNTER reaches the value 9, which is equivalent to the numbers of matrix rows preset by means of the jumpers at the inputs of the ROW DECoder, the COLumn COUNTER will be increased if $ENL=0$ and the nozzle returned to its starting position during a time determined by the one-shot NOZZLE RETURN. During the times NOZZLE RETURN and START DELAY the printing is stopped by means of the strobe input of the MULTiplexer. Due to the increase of the COLumn COUNTER, the MULTiplexer will hereafter connect the second column of the matrix to the intensity modulation electrode. Thus after the restarting of the oscillation and START DELAY this column will be printed. When the COLumn COUNTER reaches a value equal to the number of columns in the matrix preset by means of the jumpers at the inputs of the COLumn DECoder, the output of the decoder will reset the COLumn COUNTER and the PRINT flip-flop, as well as transmit a CHAracter Done signal to the control unit.

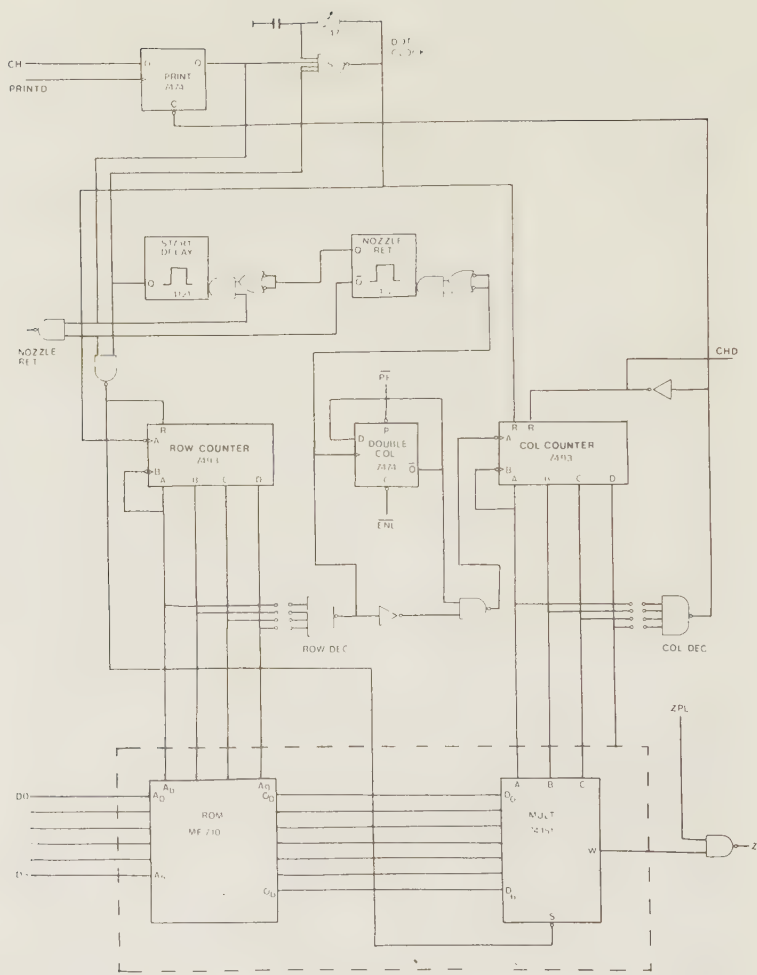


Figure 9.13. Circuit diagram of the character generator.

To facilitate changes in the matrix size, the circuits inside the dotted line are mounted on a special board. In fig. 9.14, the circuits used for a 5×7 matrix are shown.

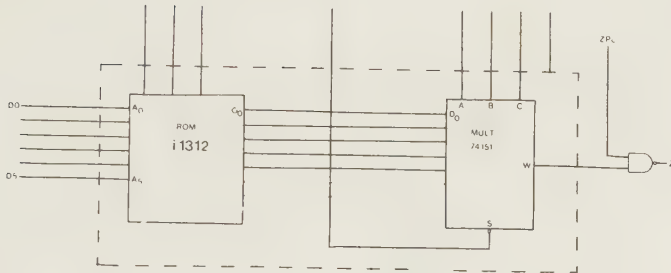


Figure 9.14. Circuits for 5×7 matrix characters.

When the typewriter works in the ENLarged character mode, each column will be printed by two rising parts of the sawtooth shaped oscillation. At the same time the number of steps by the step motor will be increase. The double printing of each of the columns is governed by the flip-flop DOUBLE COLUMNS, which prevents each second pulse from the ROW DECoder from reaching the COLUMN COUNTER, but not the one-shot NOZZLE RETURN.

9.9. Print head control

Besides the control voltage amplifier, previously described in chapter 2.3, the print head control unit contains the nozzle oscillation generator (cf. 8.3) shown in fig. 9.15.

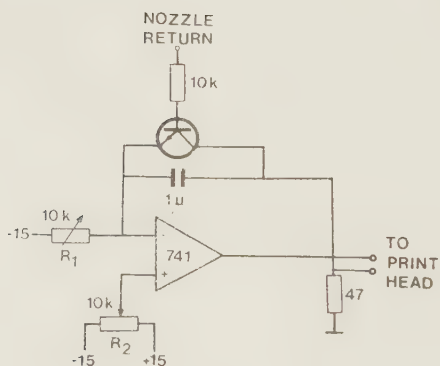


Figure 9.15. Nozzle oscillation generator.

The potentiometer R_1 is used to adjust the height of the characters while potentiometer R_2 determines their vertical position.

9.10. Results

The present ink jet typewriter has been used with a set of 5×7 matrix characters as well as 7×9 matrix characters. The limiting factor of the print rate in both cases was shown to be the step rate of the motor moving the print head, or more precisely, its start, run and stop characteristics.

Since the print rate is limited to 50 characters/s by the step motor in the present typewriter, sawtooth shaped oscillations of the nozzle can be used. If the print rate shall be increased by means of a better step motor and carriage of the print head, this shape of oscillation cannot be used any more. Instead, either sine or triangular shaped oscillations have to be used.

If 5×7 matrices are used for the character representation, the nozzle will have to oscillate at a frequency of about 300 Hz at a print rate of 50 characters/s to give a suitable spacing between the characters. In fig. 9.16 a print sample is shown, made on the typewriter using a 5×7 character matrix. The print out is controlled by a computer, because of which the sample was printed at the highest possible rate, 50 characters/s. The two top lines: "Ink jet typewriter" and the line of stars are made with the typewriter in the "enlarged character" mode, previously described. The change from "enlarged character" mode to "normal character" mode is controlled by the computer, by means of the character control 0 and control N. The character densities of the print out are 10 characters/inch in the case of normal sized characters and 3.5 characters/inch when the typewriter is operated in the "enlarged character" mode.

In the case of 5×7 matrix characters, a character density of 12 characters/inch can be used preferably. This higher character density and by that shorter distance between the columns of the matrix, will make the ink traces of the different columns overlap because of which they are not so apparent, as can be seen in fig. 9.17.

INK JET TYPEWRITER
* * * * *

TECHNICAL DESCRIPTION

THIS TECHNICAL NOTE HAS BEEN TYPED ON A TYPEWRITER WHICH USES A SINGLE INK JET AS A WRITING ELEMENT. THE JET IS INTENSITY MODULATED ACCORDING TO A METHOD DEVELOPED AT THE DEPARTMENT OF ELECTRICAL MEASUREMENTS, LUND INSTITUTE OF TECHNOLOGY. THE JET IS PRODUCED BY AN ELEMA SCHONANDER GALVANOMETER WHICH CONSTITUTES THE PRINTING HEAD. THE TYPEWRITER ALLOWS MANUAL TYPING OR CONTROL BY A MINICOMPUTER WITH A MAXIMUM SPEED OF 50 CHARACTERS/SECOND AND WORKS ABSOLUTELY SILENTLY.

Figure 9.16. Sample printed by ink jet typewriter using a 5 x 7 matrix (10 characters/inch).

I N K J E T T Y P E W R I T E R
* * * * *

TECHNICAL NOTE

THIS TECHNICAL NOTE HAS BEEN TYPED ON A TYPEWRITER WHICH USES A SINGLE INK JET AS A WRITING ELEMENT. THE JET IS INTENSITY MODULATED ACCORDING TO A METHOD DEVELOPED AT THE DEPARTMENT OF ELECTRICAL MEASUREMENTS, LUND INSTITUTE OF TECHNOLOGY. THE JET IS PRODUCED BY AN ELEMA SCHONANDER GALVANOMETER WHICH CONSTITUTES THE PRINTING HEAD. THE TYPEWRITER ALLOWS MANUAL TYPING OR CONTROL BY A MINICOMPUTER WITH A MAXIMUM SPEED OF 50 CHARACTERS / SECOND AND WORKS ABSOLUTELY SILENTLY.

Figure 9.17. Sample printed by ink jet typewriter using a 5 x 7 matrix (12 characters/inch).

However, if 7×9 matrices are used for the character representation, the higher character density is not needed to ensure overlapping of the ink traces of the characters. Besides that, the use of a larger character matrix will make the characters more perfect in form as can be seen from fig. 9.18. This sample was printed using the same parameters as that of the sample in fig. 9.16, except for the size of the character matrix.

Since the difference in cost between a Read Only Memory (ROM) containing a set of 5×7 matrix characters or 7×9 matrix characters is small, the only occasion to use the smaller matrix is when the print rate is limited, not by the movement of the print head as in this case, but by the oscillation frequency of the ink jet nozzle.

The sample in fig. 9.18 is also printed under computer control at a rate of 50 characters/s. However, the first character of each line has the same appearance as if it was printed at a lower rate, since the print head in this case is accelerated from a stationary state. This is apparent from a closer study, which reveals that the first character of each line is somewhat wider. Besides that the first character of each line is not quite symmetrical, the left half of the character being somewhat compressed compared with the right half. This is especially apparent for the character "T".

Both these unwanted effects can be explained by means of fig. 9.3 in the chapter "The moving of the print head". The compression of the left half of the characters when the printing starts with the print head in a stationary state, is caused by the fact that the print head is not quite accelerated to its final velocity at the start of the print out.

Since the actual print out occurs during a specific time interval "print ch" and not a distance, the width of the characters will be dependent on the velocity of the print head. From the fig. 9.3. it can be seen that, if the print head is started from stationary, the

I N K J E T T Y P E W R I T E R * *
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* * * * *

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Figure 9.18. Sample printed by ink jet typewriter using a 7 x 9 matrix (12 characters/inch).

width of the first character, equal to the distance "character 1" will be about 10% larger than if the print head is already moving before the start of the actual printing as in the case of "character 2".

If the ratio between the start delays τ_1 and τ_2 in fig. 9.3 is not correctly adjusted, the spacing between the characters when the typewriter switches from asynchronous to synchronous operation will not have the correct value. This can be observed after the first character of each line in the sample in fig. 9.19. From this sample it is also evident that the characters will be somewhat wider when the print head has to be accelerated, as in the case of the manually typed characters after each question-mark.

```
-----  
WHAT CLUB DO YOU WANT ? 1  
SHOT WENT 237YARDS - IS 135YARDS FROM HO  
BALL IS 17YARDS OFF LINE IN FAIRWAY  
WHAT CLUB DO YOU WANT ? 3  
TOO MUCH CLUB YOU ARE PAST HOLE  
YOU SLICED-SHOT WENT 222YARDS - IS 104YA  
BALL IS 39YARDS OFF LINE IN ADJACENT FAI  
WHAT CLUB DO YOU WANT ? 19  
ON GREEN 54FEET FROM PIN. PUT POTENCY NU  
YOU H*O*LKE*E*E* IT  
YOUR SCORE ON HOLE 1 WAS 4  
A PAR NICE GOING
```

Fig. 9.19. Print sample of 7 x 9 matrix characters, where the ratio between the start delays τ_1 and τ_2 are misadjusted.

A way to circumvent the problem of the spacing between the characters as well as the columns of a character should be to use a shaft encoder mounted on the axis of the step motor, the signals from which would control the printing of each column of the characters.

If such a system was used, the control of the character width as well as the spacing ought to be simple.

However, at the nozzle oscillation frequencies used, 300 - 400 Hz, the time interval τ_s in fig. 9.20 between two periods of nozzle oscillation cannot be varied without changing the pattern of the mechanical oscillation during the printing of a matrix column. Thus the use of a shaft encoder would probably be successful only if the print rate is low enough to let the jet nozzle come to rest between the printing of two successive columns.

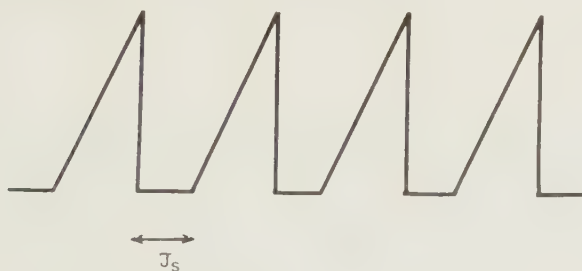


Figure 9.20. Electrical signal to control a sawtooth oscillation of the ink jet nozzle.

If the print head is moving at a constant velocity, the width of the characters is mainly determined by the clock in the character generator (fig. 9.13), controlling the information transmission between the ROM and the control electrode of the print head. By changing the clock frequency the width of the characters can be varied. The height of the characters can easily be varied by means of potentiometer R_1 in the integrator of the print head control (fig. 9.15). This is demonstrated in fig. 9.21, where print samples of 5×7 matrix characters are shown, the size of which is varied in this way. In sample a) the characters are perhaps too small for normal applications, while in sample c) the width of the characters is too large, making the spacing between the characters almost disappear. The samples d) and e) are made with a character density of 10 characters/s, because of which a larger size of

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- a)

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- b)

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- c)

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Figure 9.21. Print samples of 5 x 7 matrix characters
(print rate 50 ch/s)
a - c) 12 characters/inch
d - e) 10 characters/inch

THE GAME OF 21 AS MANY AS 7 PLAYER
ON EACH DEAL. BETS WILL BE ASKED FOR
a) 'BETS SHOULD BE TYPED IN THE CARDS
AND EACH PLAYER IN TURN PLAYS HIS HAND
E SHOULD BE EITHER 'D', INDICATING TH

THIS IS THE GAME OF 21 AS MANY AS 7
GAME ON EACH DEAL, BETS WILL BE ASK
b) PLAYERS' BETS SHOULD BE TYPED IN. TH
DEALT, AND EACH PLAYER IN TURN PLAYS
RESPONSE SHOULD BE EITHER 'D', INDICA

S TECHNICAL NOTE HAS BEEN TYPED ON A T
c) GLE INK JET AS A WRITING ELEMENT. THE
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GLE INK JET AS A WRITING ELEMENT. THE
d) ATED ACCORDING TO A METHOD DEVELOPED A
ELECTRICAL MEASUREMENTS, LUND INSTITUTE

Figure 9.22. Print samples of 7 x 9 matrix characters
(print rate 50 ch/s
character density 10 characters/inch

the characters was selected. In fig. 9.22 the size of 7 x 9 matrix characters is varied instead.

Larger character matrices than 7 x 9 have not been tried in the typewriter at present, but the design of the present typewriter allows the installation of other matrix sizes easily. However, at printing 50 7 x 9 matrix characters per second the ink jet nozzle oscillates already at its highest possible frequency of a sawtooth shaped oscillation. If character matrices containing more than 7 columns are to be used, either the maximum print rate has to be decreased or another shape of oscillation has to be used.

Both the character sets used contain only large characters. At the start of this project, ROMs containing small characters were not commercially available, consequently a key-board, having a standard Teletype configuration without small characters was selected. Thus, to be able to print even small characters with the present typewriter, both the key-board and the ROM have to be changed. This has not been done yet. However, if this extension is to be accomplished, special care has to be taken with five of the small characters. In fig. 9.23 is shown the normal way of representing some of the small characters by means of 7 x 9 matrices.

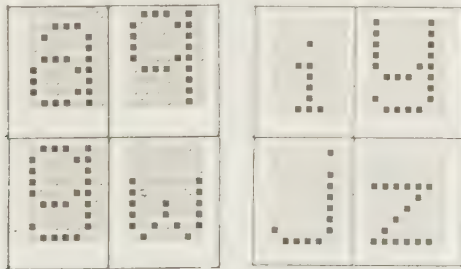


Figure 9.23. The representation of the small characters by means of 7 x 9 matrices.

As can be seen the characters g, j, p, q, y have to be displaced 3 matrix rows downwards to be correctly situated. This can be implemented easily. Each time the character to be printed is recognized as one of the above by some means, a suitable voltage is added to the integrator in the print head control. By this the zero line of the nozzle oscillation will be displaced downwards on the paper, and likewise the whole print out of this character.

Besides alfa-numerical printing, the typewriter can be used in a graphical mode, during which it acts as an x-y plotter. As previously mentioned, the rotation of the heavy platen was problematic, especially since no step motor could be used because of space considerations. However, in fig. 9.24 a print sample containing a diagram is shown. The print time of the diagram was about 15 s, but can be decreased appreciably if a better system to move the platen is developed.

INK JET TYPEWRITER

CONVERT AN ASCII CHARACTER STRING TO A SINGLE PRECISION BINARY NUMBER CONVERTS AN ASCII DECIMAL CHARACTER STRING TO A TWO'S COMPLEMENT, FIXED POINT, BINARY NUMBER INPUT. CALLS A GET CHARACTER ROUTINE WHOSE ADDRESS MUST BE STORED IN LOCATION 40 OF PAGE 0 CHARACTER S MUST BE RETURNED RIGHT ADJUSTED IN AC0 WITH BIT 8-0 + IS OPTION AL FOR POSITIVE NUMBERS - MUST BE GIVEN FOR NEGATIVE NUMBERS INPUT OF FORM: SDD D(BREAK) S IS THE SIGN, D A DECIMAL DIGIT THE BREAK CHARACTER IS ANY CHARACTER OTHER THAN A DIGIT. OUTPUT: AC0 CONTAINS THE BREAK CHARACTER AC1 CONTAINS THE BINARY INTEGER CALLING SEQUENCE JSR DBIN RETURN IF AN INDICATION IS DESIRED TO SIGNAL NCE IS JSR DBIN RETURN AN ASCII S FOR LLOWED BY A NULL WORD WILL BE TRANSMITTED VIA AC0 TO A PUT CHARACTER ROUTINE WHOSE ADDRESS MUST BE IN LOCATION 41 OF PAGE 0 CAUTION: THE ABSOLUTE VALUE OF THE R741 CONVERTS TO +31205 -2*15 CONVERTS TO 0 DESTROYED: AC0, AC1 UNCHANGED: AC2, A NCE IS JSR DBIN RETURN AN ASCII S FOR LLOWED BY A NULL WORD WILL BE TRANSMITTED VIA AC0 TO A PUT CHARACTER ROUTINE WHOSE ADDRESS MUST BE IN LOCATION 41 OF PAGE 0 CAUTION: THE ABSOLUTE VALUE OF THE R741 CONVERTS TO +31205 -2*15 CONVERTS

CONVERT AN ASCII CHARACTER STRING TO A SINGLE PRECISION BINARY NUMBER CONVERTS AN ASCII DECIMAL CHARACTER STRING TO A TWO'S COMPLEMENT, FIXED POINT, BINARY NUMBER INPUT. CALLS A GET CHARACTER ROUTINE



FIG 1 RESULT

Figure 9.24. Print sample containing a diagram, printed with the typewriter in the graphical mode.

APPENDIX

Measurements of the parameters of the ink jet

1. Measurements of the diameter d_o of the jet.

The diameter d_o of the ink jet can be measured in the following way.

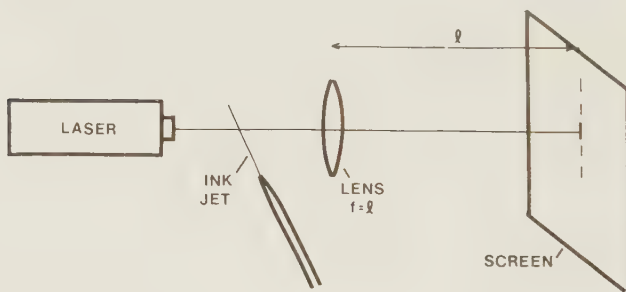


Figure A.1. Measurements of the jet diameter d_o .

If an ink jet is situated in a laser beam, as shown in fig. A.1, the interception of the beam by the jet will cause Fraunhofer diffraction of the light to appear on the screen.

The equation normally used for Fraunhofer diffraction caused by a single slit can be applied on this diffraction pattern too. The diameter, equal to the width of the slit, is given by Jenkins (1950):

$$d_o = \frac{n \cdot \lambda}{\sin(\arctan y/l)} \quad (A.1)$$

where y is the distance of the n th minimum from the axis of the laser beam on the screen.

The diameter measured in this way is the diameter of the jet and not that of the nozzle, which will be about 15% larger due to contraction of the jet (Harmon 1955).

2. Measurements of the initial velocity v_0 of the jet.

The volume flow Q of a nozzle can easily be measured by weighing the amount of ink ejected per second. In fig. A.2 the volume flow Q is shown as a function of the jet diameter d_0 at a pressure of 47 kg/cm^2 .

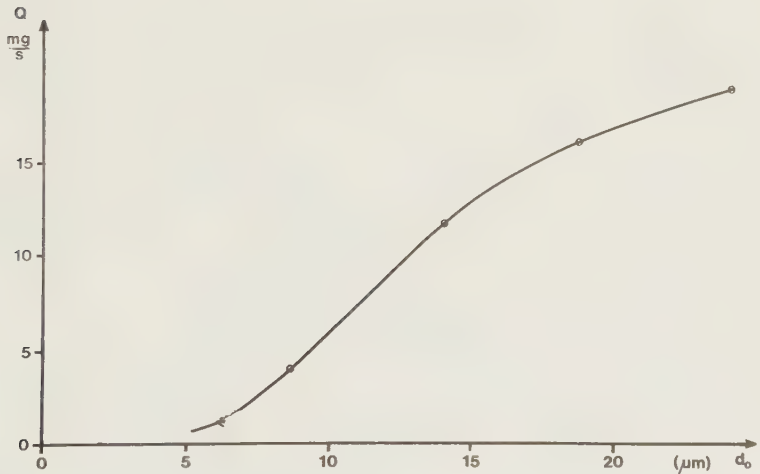


Figure A.2. The volume flow Q as a function of the jet diameter d_0 at a pressure of 47 kg/cm^2 .

These measurements can also be used to calculate the initial velocity v_0 of the jet. Since the volume flow Q can be expressed as:

$$Q = \frac{v_0 \cdot \frac{\pi}{4} d_0^2 \cdot \pi}{L} \cdot \rho \quad (\text{A.2})$$

the initial velocity v_0 is given by:

$$v_0 = \frac{L \cdot Q}{\pi \cdot \rho \cdot d_0^2} \quad (\text{A.3})$$

Fig. A.3 shows the relationship between the pressure P_0 applied to the ink container and the initial velocity.

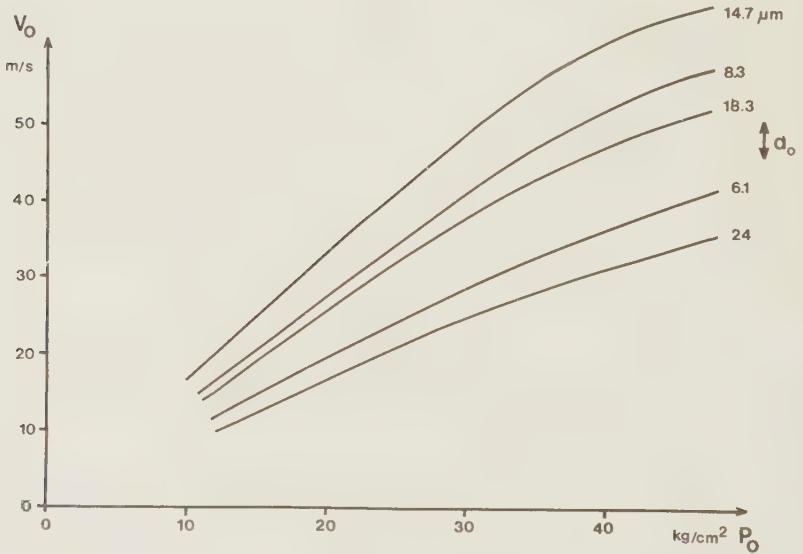


Figure A.3. The initial velocity as a function of the ink pressure P_0 .

3. Measurements of the drop formation point.

When designing an electrode system for intensity modulation, the point where the jet breaks up into drops is of special interest. This drop formation point has to be situated close to or inside the charging electrode (cf. 2.2) to ensure proper charging of the drops. Further, the charging electrode should also ensure electrical shielding from the deflection field.

The distance between the nozzle tip and the drop formation point can easily be measured with a microscope by illuminating the jet by a laser beam. If the laser beam hits the jet at the correct angle, the unbroken jet will be dark but the drop train appears light, due to different reflection and scattering properties of their respective geometrical shapes.

In fig. A.4 the distance L_0 from the nozzle to the drop formation point is shown for different jet diameters d_0 at different pressures P_0 .

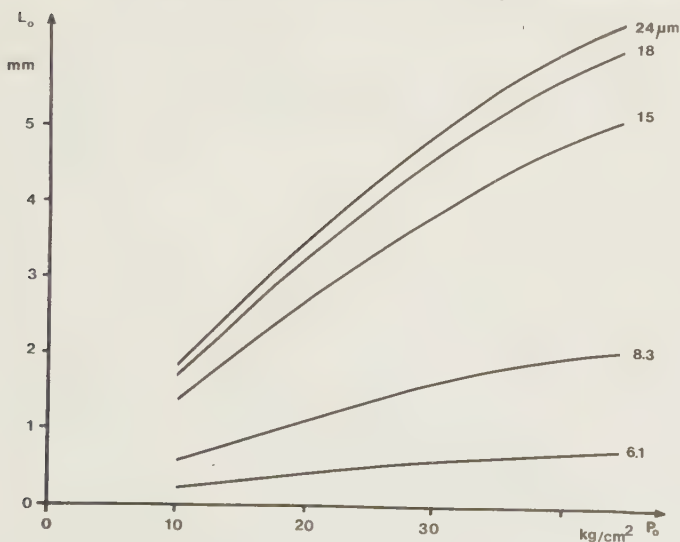


Figure A.4. The distance L_0 between the nozzle tip and the spontaneous drop formation point of jets of different diameters d_0 .

These measurements correlate very well with a theoretical equation given by Weber (1931):

$$L_o = 12 \cdot v_o \cdot \left(\frac{d_o^3 \cdot \rho}{\sigma} \right)^{\frac{1}{2}} \quad (A.4)$$

in which v_o is the mean jet velocity, d_o the nozzle diameter, the liquid density and the surface tension.

For the ink used in this report the following values are valid:

$$\rho = 1.05 \cdot 10^3 \text{ kg/cm}^2$$

$$\sigma = 73 \cdot 10^{-3} \text{ N/m}$$

The correlation between the measured and the theoretical values is so good that the position of the drop formation point can be used as a simple method for measuring relative changes in the initial velocity v_o of an ink jet.

ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to Dr. Hellmuth Hertz, head of the Department of Electrical Measurements, Lund Institute of Technology, under whose stimulating guidance this work was carried out. The inspiring atmosphere created by the colleagues of the department, especially Dr. Åke Månsson, was of great importance for my work.

Appreciation and thanks are expressed to Mr. Lennart Nilsson and his colleagues at the workshop for their assistance in mechanical problems.

I am greatly indebted to Mrs. Margaret Jansson and Mrs. Anita Borné for typing the manuscript.

I also wish to take the opportunity to thank Siemens-Elema AB, Stockholm, for supplying the ink and nozzles necessary to generate the jets.

REFERENCES

- Borne, J High speed printers for numerical data processing equipment.
Philips Techn Rev, vol 29, 1968, p 205.
- Brewster, A E A high-speed magnetic print out system.
Electronics and Power, vol 62, 1968.
- Carroll, F E Technology of computer output printing devices.
Arriot, R A Seminar on Computer Handling of Graphical Information, Newton, Mass, 1970.
- Cramer, B Printing data terminal: The new LO 380 system.
Electrical Communication, vol 45, No 3, 1970.
- Currah, J E Electrolytic recorder paper.
Arthur, E M S Ind Eng Chem, vol 39, 1948, pp 1286-1288.
Thiers, R E E
McBryde, W A E
Beamish, F E
- Erikson, R B Tryckverk för tipskuponger.
Report 1/1974 Dept El Measurem, Lund Inst of Technology.
- Erikson, R B Ink jet address printer.
Månsson, Å To be published.
- Erikson, R B Registrering av ultraljudskardiogram med intensitetsmodulering av bläckstråleskrivare.
Gudmundsson, B Report 1970, Dept El Measurem. Lund Inst of Technology.
- Ernbo, A Character printing with intensity-modulated ink jets.
Report 1/1973, Dept El Measurem, Lund Inst of Technology.
- Ewing, G W Instrumental methods of chemical analysis.
New York: McGraw-Hill 1969.

- Harmon, D B Drop sizes from low speed jets.
J Franklin Institute, vol 259, 1955, p 519.
- Hertz, C H
Månsson, Å
Simonsson, S I A method for the intensity modulation of a
recording ink jet and its applications.
Acta Univ Lundensis, Sec II, vol 15, 1967, p 1.
- Hertz, C H
Simonsson, S I Ink jet recorder.
US Patent 3 416 153, Dec 10, 1968.
- Higgins, G C
Jones, L A Evaluation of image sharpness.
J Soc Mot Pict Telev Engrs, vol 58, 1952, pp 277-290.
- Härtel, W
Degenhart, J
Kübler, A
Sörensen C
Träger J Lichtstrahl-Oszillographen
München: Oldenburg 1961.
- Jenkins, F
White, H Fundamentals of optics.
New York: McGraw-Hill 1950.
- Jonsson, B
Erikson, R B
Gustavsson, S
Jansson, L
Johansson, K
Olsson, L G
Werner, O A system to facilitate the recording,
presentation and storage of ECG.
Symposium on computer processing of ECG,
Umeå, Oct 18-19, 1974.
- Kamphoefner, F J Ink jet printing.
IEEE Trans El Dev, vol ED-19, April 1972,
pp 584 - 593.
- Lindström, K
Holmer, N G
Erikson, R B
Gudmundsson, B The recording of Echocardiograms with an
intensity-modulated ink jet oscillograph.
IEEE Trans Biom Eng, vol BME-20, No 6,
Nov 1973, pp 421-426.
- Mees, C E K
James, T H The theory of the photographic process.
New York: MacMillan Company 1966.
- Månsson, Å Investigation of electrically charged liquid jets.
Physica Scripta 1971.

- Månsson, Å Electric control of fluid jets, theory and application to image generation.
Report 1/1972, Dept El Measurem, Lund Inst of Technology.
- Olivei, Å A new nonimpact printing technique for alphanumeric characters.
IEEE Trans Electron Dev, vol ED-19, No 4, April 1972, pp 594-616.
- Payne, T R Thermal printer.
Plumlee, H R IEEE J of Solid State Circuits, vol SC-8, No 1, February 1973, pp 71-78.
- Lord Rayleigh On the instability of jets.
Proc Lond Math Soc, vol 10, 1879, p 4.
- Sima, H. Flüssigkeitsstrahl Oszillographen.
Elektronik, vol 15, 1966, pp 213-214.
- Smeds, B A 3-color ink jet plotter for computer graphics.
BIT, vol 13, No 2, 1973, pp 181-195.
- Stone, J J The videograph electrostatic printing process.
IEEE Trans El Dev, vol ED-19, No 4, april 1972.
- Sweet, R C Electrostatic graphic recording.
Inst and Control Systems, vol 11, 1968, p 80.
- Weber, C Zum Zerfall eines Flüssigkeitsstrahles.
Zeitschrift f angew Math und Mech, vol 11:2, 1931, p 136.

REFERENCES ON INK JET PRINTING

- Ascoli, E Procédé d'écriture HWP par émission et
déflexion électrostatique d'un jet d'encre.
Ind Org, No 4, 1968.
- Bodenstein, C Der Tintenstrahlschreiber als Hard-Copy-
Otto, R Drucker für Datensichtgeräte.
Feinwerk Technik, Heft 9, Sept 1971, pp 365-396.
- Elmqvist, R Ink jet recorder.
US Patent 2 566 443, 1951.
- Ernbo, A A new principle for a fast print out system.
Hertz, C H Ark f fysik, vol 40, 1969, p 215.
- Ernbo, A Application of intensity-modulated ink jets
to alphanumeric printing devices.
IEEE Trans on Computers, vol C-21, 1972,
pp 942-947.
- Hertz, C H Intensity modulation of ink-jet oscillographs.
Simonsson, S I Med & Biol Eng, vol 7, 1969, p 337.
- Hertz, C H Electronic control of fluid jets and its applica-
Månsson, Å tion to recording devices.
Rev Scient Instr, vol 43, 1972, p 413.
- Lewis, A M Electrically operated character printer.
Brown, A D US Patent 3 298 030, Jan 10, 1967.
- Lloyd, D S Character generation on a moving chart recorder.
Stenfors, S G Bio-Med Eng, July 1972, pp 274-277.
Roberts, J R
- Stemme, E The piezoelectric capillary injector - a new
Larsson, L G hydrodynamic method for dot pattern generation.
IEEE Trans El Dev, vol ED-20, No 1, Jan 1973,
pp 14-19.
- Sweet, R G High frequency recording with electrostatically
deflected ink jets.
Rev Sci Instr, vol 36, Jan 1965, pp 131-136.

- Sweet, R G High-frequency oscillography with electrostatically deflected ink jets.
Technical Report No 1722-1. Stanford Electronics Laboratories, Stanford University, 1964.
- Sweet, R G Fluid droplet recorder with a plurality of jets.
US Patent 3 373 437, March 12, 1968.
- Winston, C R Method and apparatus for transferring ink.
US Patent 3 060 429, Sept 4, 1951.

